Who Has Seen the WIMP? Neither You Nor I.

Daniel McKinsey

LUX Co-Spokesperson

UC Berkeley and LBNL

Neutrino seminar

Fermilab

March 24, 2016

o has seen the wind?
ther I nor you.
when the leaves hang trembling
wind is passing through.

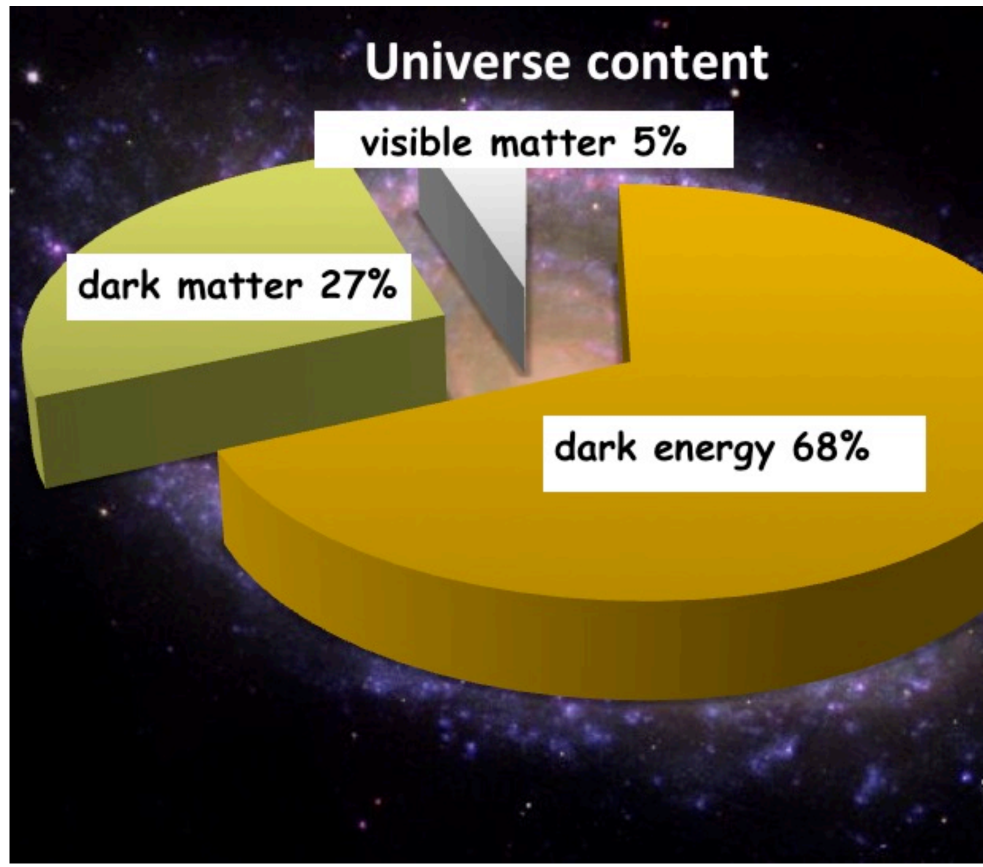
o has seen the wind?
ther you nor I.
when the trees bow down their heads
wind is passing by.

by Christina Rossetti, 1830-1894

Higgs particle has been discovered, the last piece of the Standard Mod

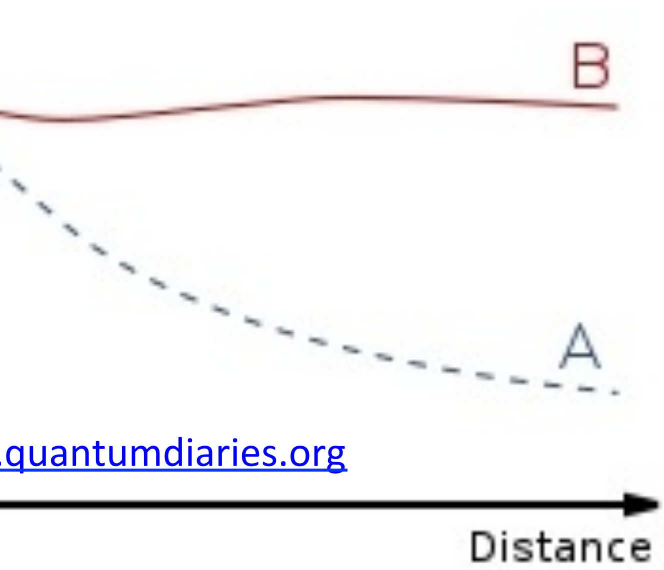
s successful as it has been, the Standard Model describes only 5% of t
erse. The remaining 95% is in the form of dark energy and dark matter,
se fundamental nature is almost completely unknown.

ray: NASA/CXC/CfA/M.Markevitch et al.;
ASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
ap: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.



www.quantumdiaries.org

axy rotation curves



The cosmic microwave backgroun

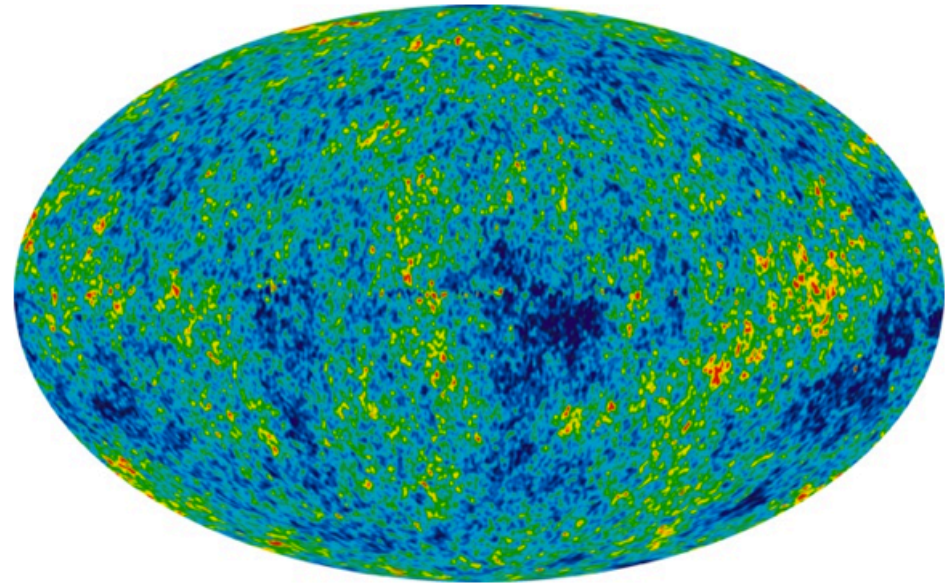
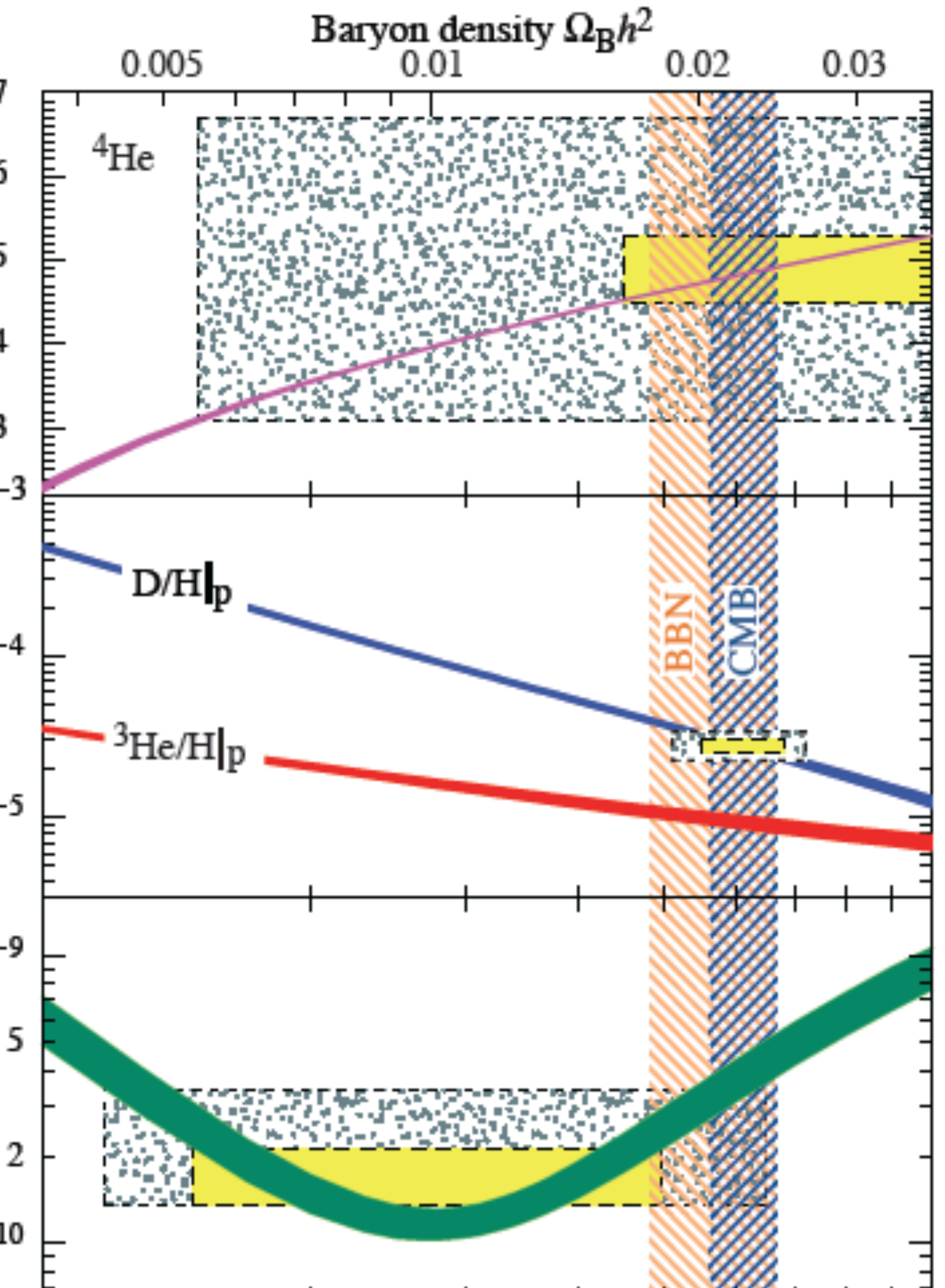


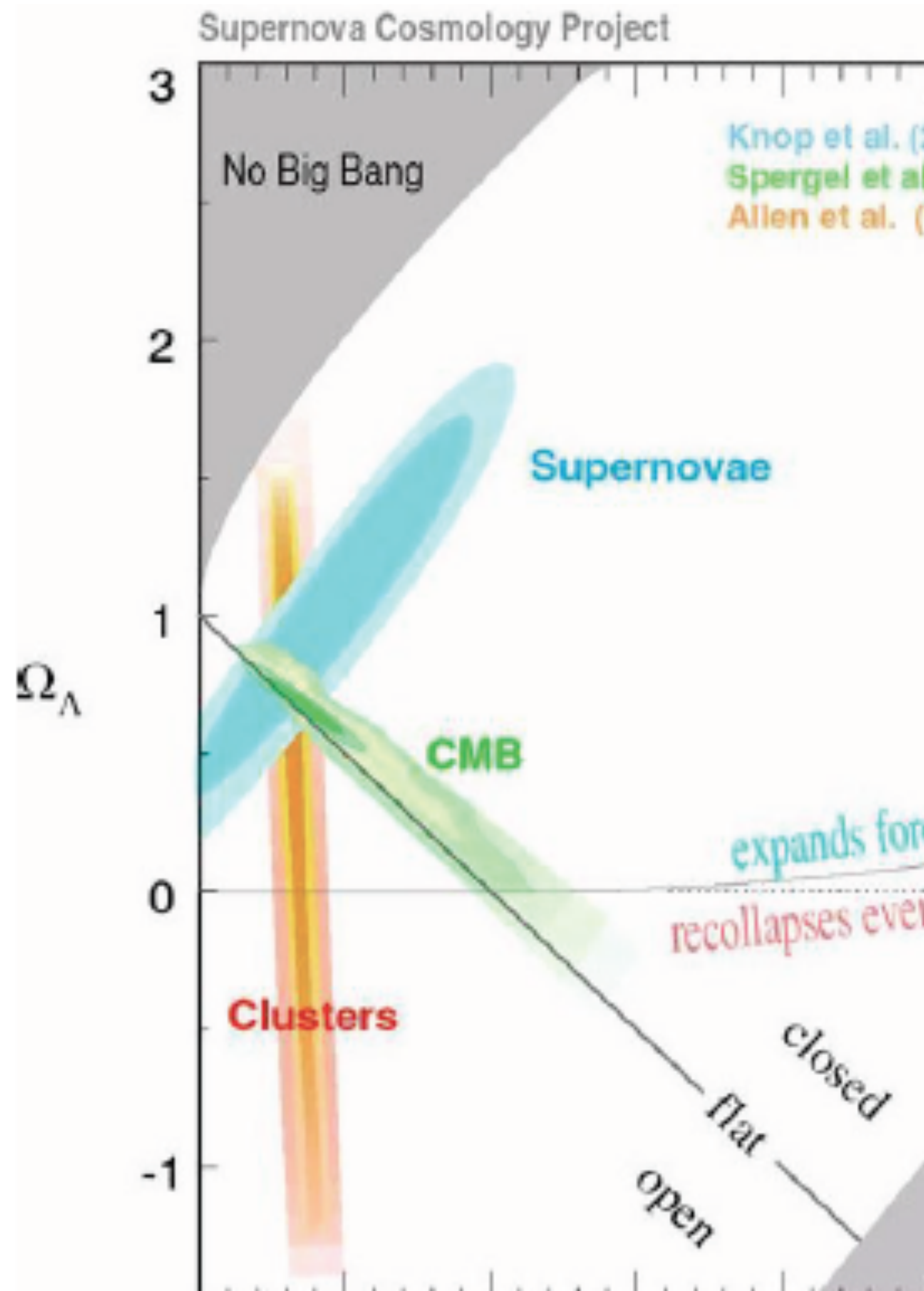
Image: ESA and the Planck collaboration

avitational lensing

- 27% of the energy composition of the univ
- Properties:
- Stable and electrically neutral
- Non-baryonic
- Non-relativistic
- Estimated local density: $0.3 \pm 0.1\,\mathrm{GeV} \cdot \mathrm{cm}^{-3}$
- Candidates: WIMPs, axions, dark photons,

Nucleosynthesis determines the density of baryons at early times; the amount of baryonic matter required is far smaller than the total quantity of matter.





article that only very weakly interacts with ordinary matter
rm Cold Dark Matter

ned in massive amounts in the Big Bang.

-relativistic freeze-out. Decouples from ordinary matter.

ld exist today at densities of about 1000/m^3.

mmetry provides a natural candidate – the neutralino.

est mass superposition of photino, zino, higgsino

s range from the proton mass to thousands of times the proton mass.

e range of cross-sections with ordinary matter, from 10^{-40} to 10^{-50} cm^2.

ge neutral and stable!

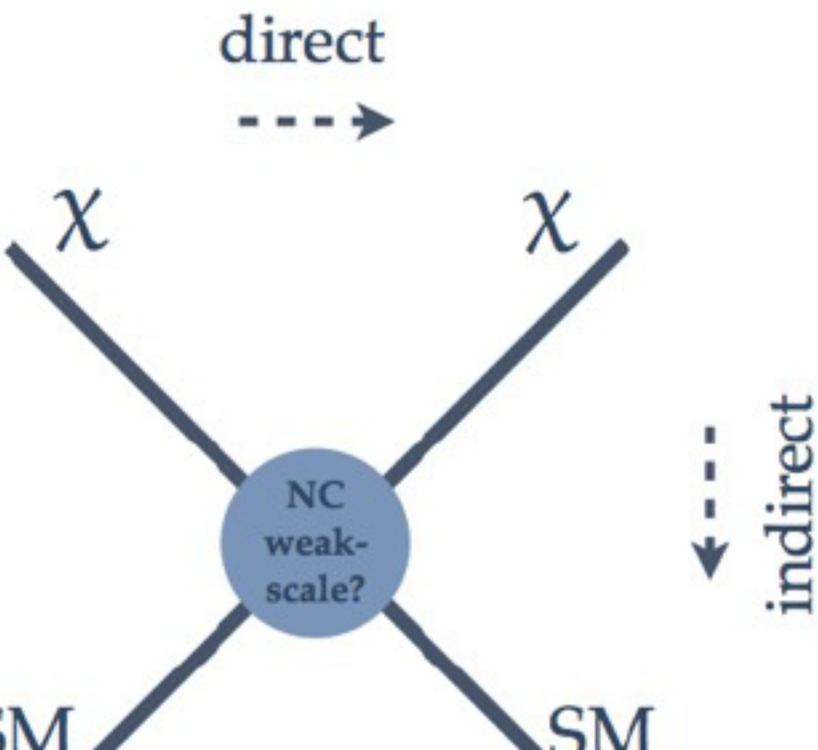
al Extra Dimensions: predicts stable Kaluza-Klein (KK) particles

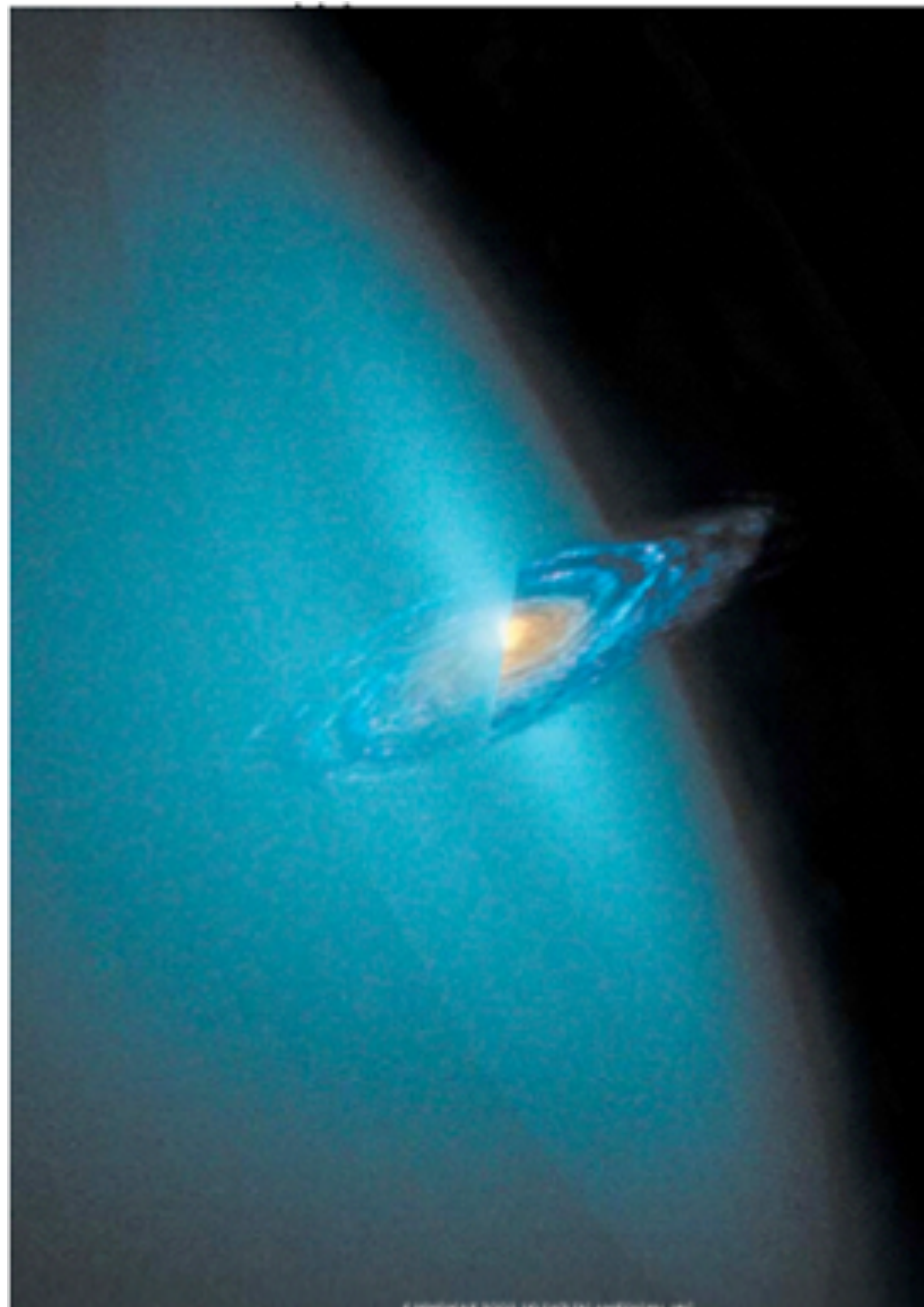
ar direct detection properties as neutralino


WIMPless DM
mSUGRA
pMSSM
Gravitino DM
Techni-
baryons
R-parity
Conserving
Asymmetric DM
Dirac DM
Q-balls
Topological DM
Theories of
Dark Matter
?
Quark
Nuggets
UED DM
6d
5d
Warm DM
RS DM
T-odd DM
Axion DM
Little Higgs

including the Milky Way

ity at Earth: ~ 300 m_{proton} / liter
$_{IMP}$ = 100 GeV, then 3 WIMPs / liter (!)
al orbital velocity = 230 km/sec
= 1/1000 speed of light
oglie wavelength is larger than nucleus:
coherent scalar scattering on ordinary
nuclear matter
cross section ~ A^2
<< 1 event/kg/(1000 days)





for anomalous nuclear recoils in a low-background detector.

N ρ<σv>. From <v> = 220 km/s, get order of 10 keV deposite

uirements:

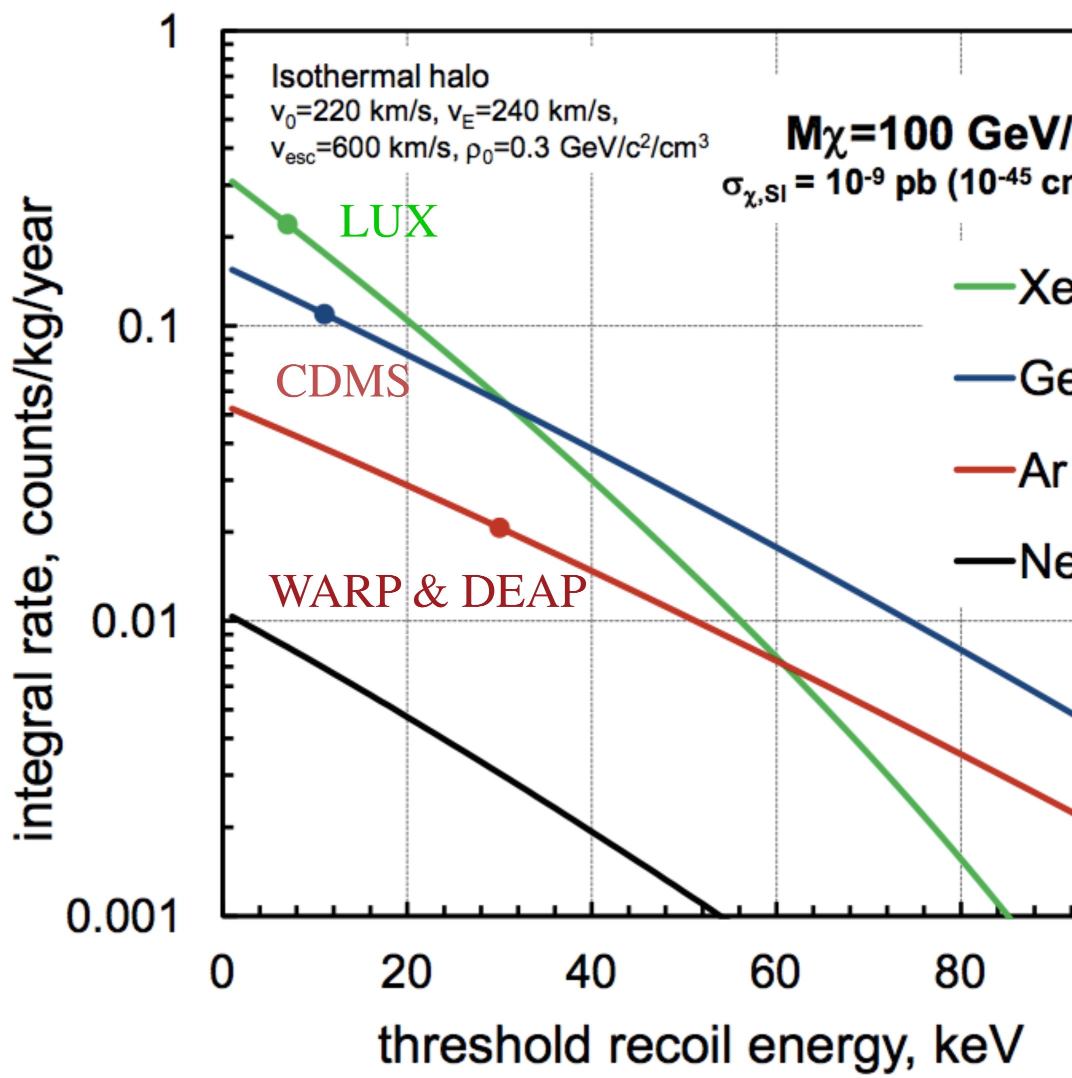
radioactivity

energy threshold

nma ray rejection

ability

p underground laboratory



The Noble Liquid Revolution

e liquids are relatively inexpensive, easy to obtain, and dens

ly purified
- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

zation electrons may be drifted through the heavier noble liqu

high scintillation yields
- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

y construction of large, homogeneous detectors

Liquified Noble Gases: Basic Properties

Dense and homogeneous

Do not attach electrons, heavier noble gases give high electron mobility

Easy to purify (especially lighter noble gases)

Inert, not flammable, very good dielectrics

Bright scintillators

Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet mol lifetime (μs)
0.145	4.2	low	80	19,000	none	13,000,0
1.2	27.1	low	78	30,000	none	15
1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
3.0	165	2200	175	42,000	^{136}Xe	0.03

	PI, Professor
	Research Associate
	Postdoc
	Graduate Student
	Graduate Student
	Graduate Student
	Graduate Student
	Graduate Student

rn

	PI, Professor
	PI, Professor
	Postdoc
	Postdoc
	Postdoc
	Graduate Student
	Graduate Student
	Graduate Student
	Graduate Student

perial College London

	PI, Reader
	Professor
	Postdoc
	Graduate Student

erkeley + UC Berkeley

	PI, Professor
	Senior Scientist
	Senior Scientist
m	Postdoc
	Scientist
	Graduate Student

ivermore

	PI, Leader of Adv. Detectors Group
	Mechanical Technician
	Staff Physicist
	Staff Physicist
	Engineer

ra

	PI, Professor
	Assistant Professor
	Senior Researcher

SD School of Mines

Xinhua Bai	PI, Professor
Tyler Liebsch	Graduate Student
Doug Tiedt	Graduate Student

SDSTA

David Taylor	Project Engineer
Mark Hanhardt	Support Scientist

Texas A&M

James White †	PI, Professor
Robert Webb	PI, Professor
Rachel Mannino	Graduate Student
Clement Sofka	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Bob Svoboda	Professor
Richard Lander	Professor
Britt Holbrook	Senior Engineer
John Thomson	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalaysay	Postdoc
Matthew Szydagis	Postdoc
Richard Ott	Postdoc
Jeremy Mock	Graduate Student
James Morad	Graduate Student
Nick Walsh	Graduate Student
Michael Woods	Graduate Student
Sergey Uvarov	Graduate Student
Brian Lenardo	Graduate Student

UC Santa Barbara

Harry Nelson	PI, Professor
Mike Witherell	Professor
Dean White	Engineer
Susanne Kyre	Engineer
Carmen Carmona	Postdoc
Curt Nehrkorn	Graduate Student
Scott Haselschwardt	Graduate Student

University College London

Chamkaur Ghag	PI, Lecturer

University of Edinburgh

Alex Murphy	PI, Reader
Paolo Beltrame	Research Fellow
James Dobson	Postdoc

University of Maryland

Carter Hall	PI, Professor
Attila Dobi	Graduate Student
Richard Knoche	Graduate Student
Jon Balajthy	Graduate Student

University of Rochester

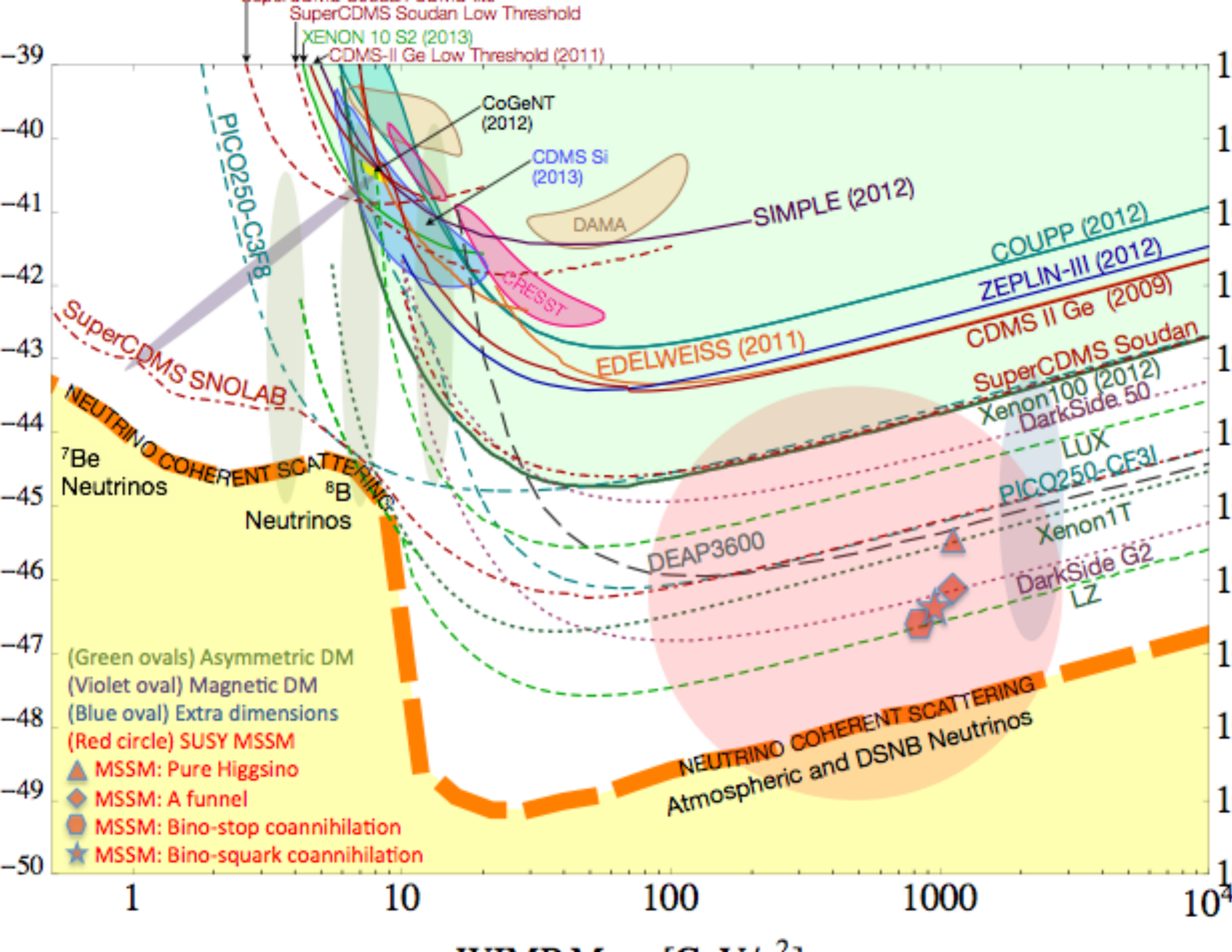
Frank Wolfs	PI, Professor
Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student

University of South Dakot

Dongming Mei	PI, Profess
Chao Zhang	Postdoc
Angela Chiller	Graduate S
Chris Chiller	Graduate S
Dana Byram	*Now at SD

Yale -> UC Berkeley

Daniel McKinsey	PI, Profess
Peter Parker	Professor
Sidney Cahn	Lecturer/Re
Ethan Bernard	Postdoc
Markus Horn	Postdoc
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Nicole Larsen	Graduate S

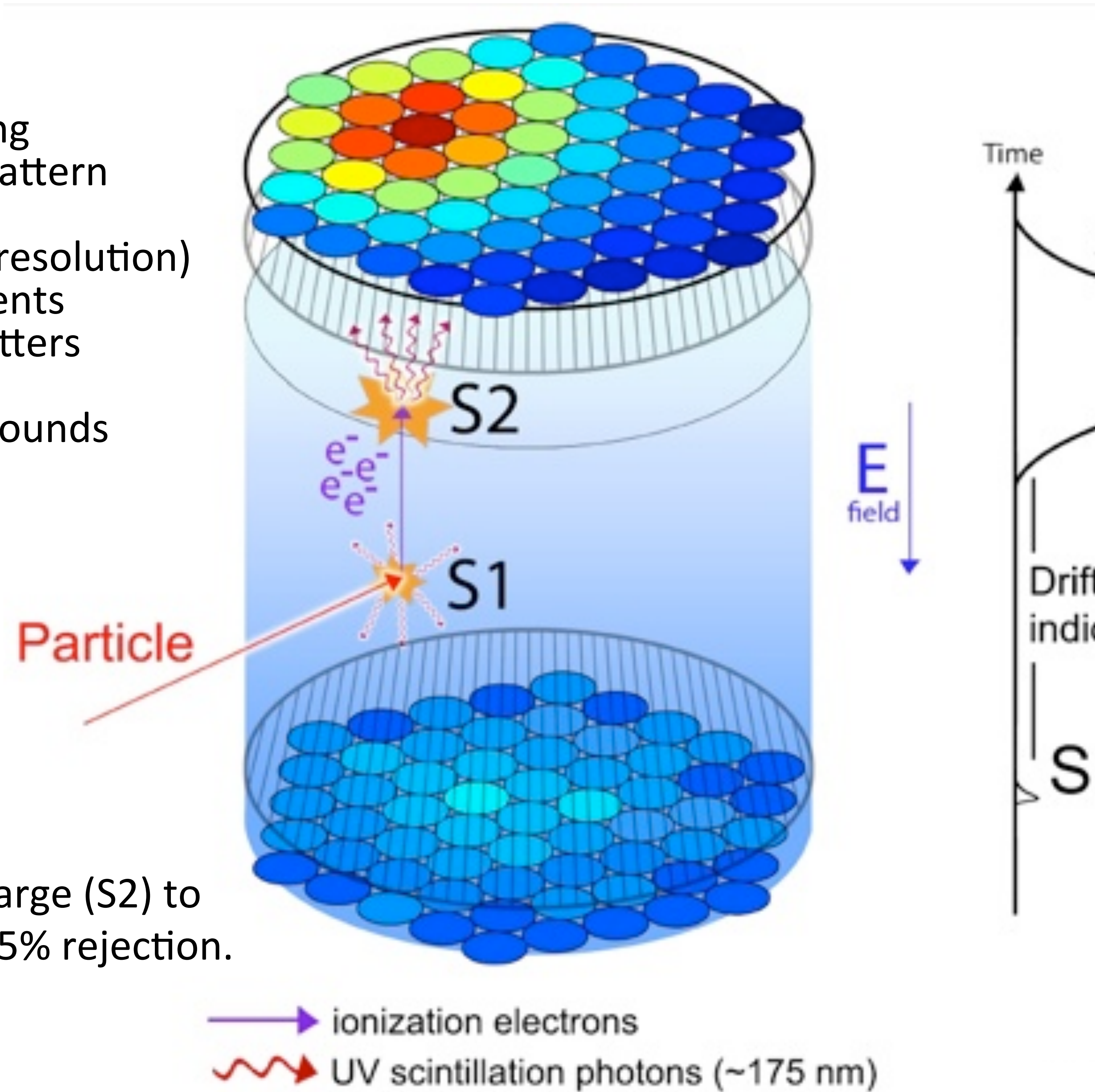


SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
PICO250-C3F8
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
-39
-40
-41
-42
-43
-44
-45
-46
-47
-48
-49
-50
1
10
100
1000
10^4

on from S1 – S2 timing
itions from S2 light pattern

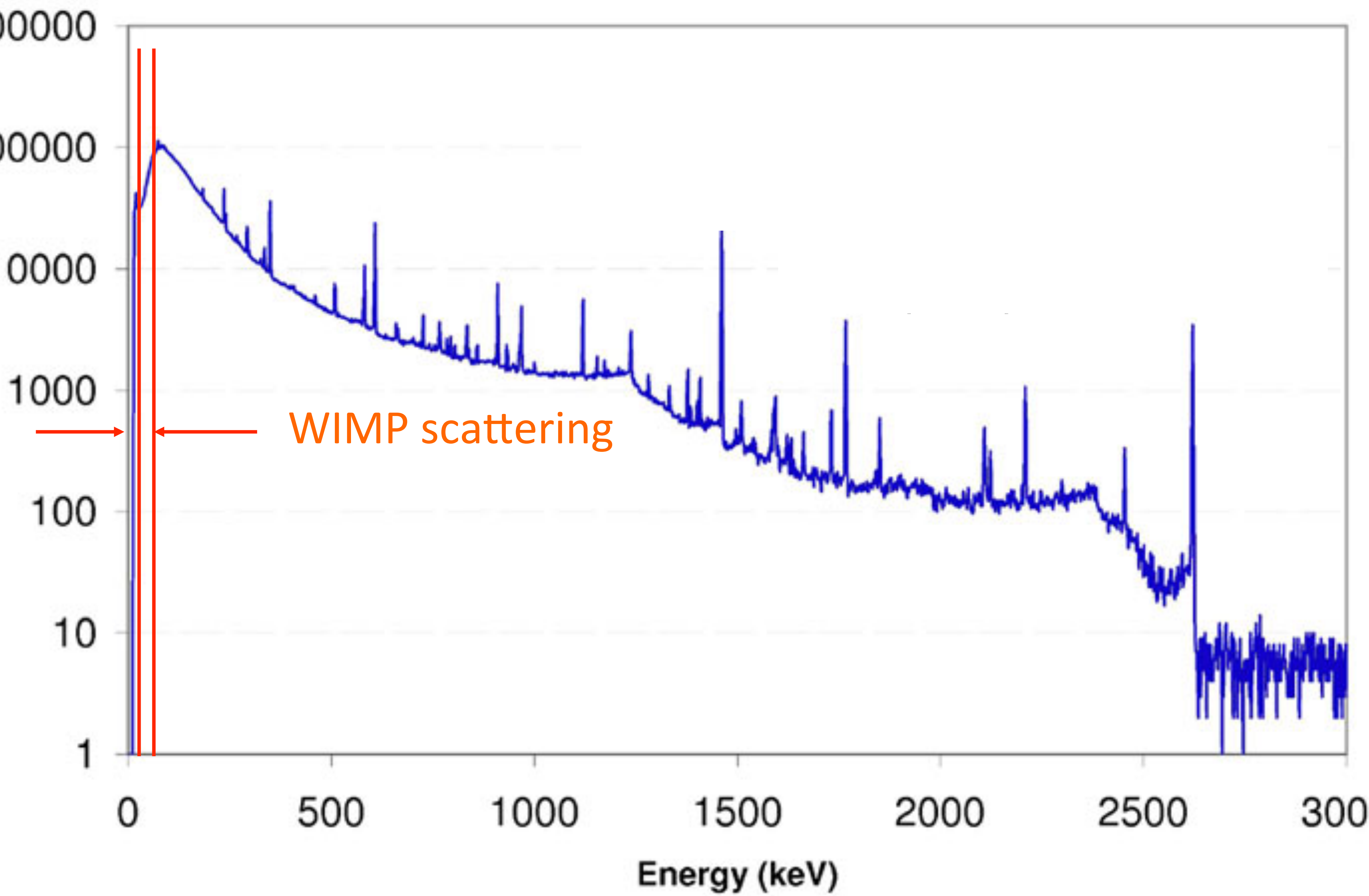
nt 3D imaging (~mm resolution)
- eliminates edge events
- rejects multiple scatters

a ray, neutron backgrounds
d by self-shielding



gammas, betas by charge (S2) to
1) ratio. Expect > 99.5% rejection.

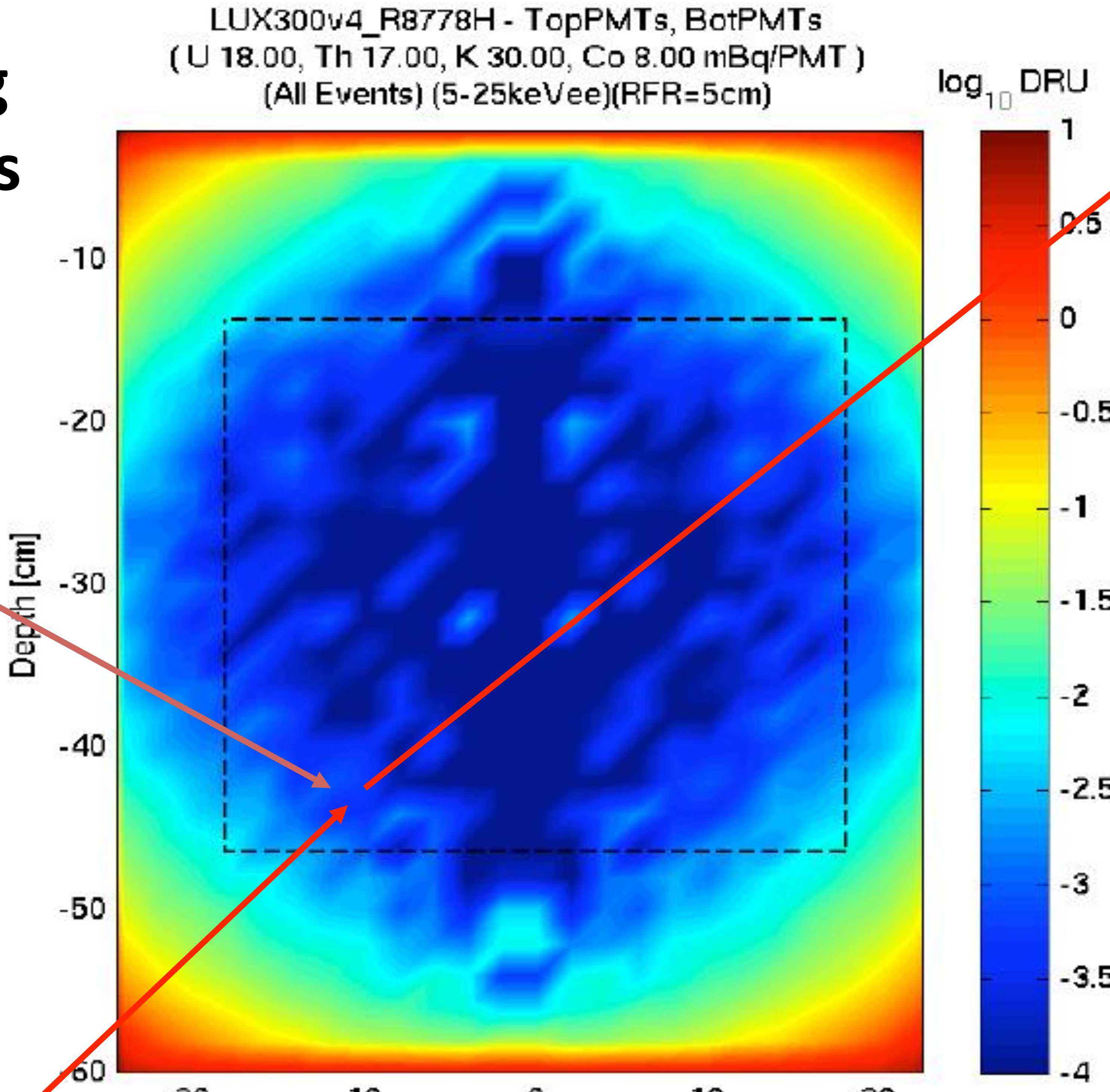
ordinary radioactive decay here on ear



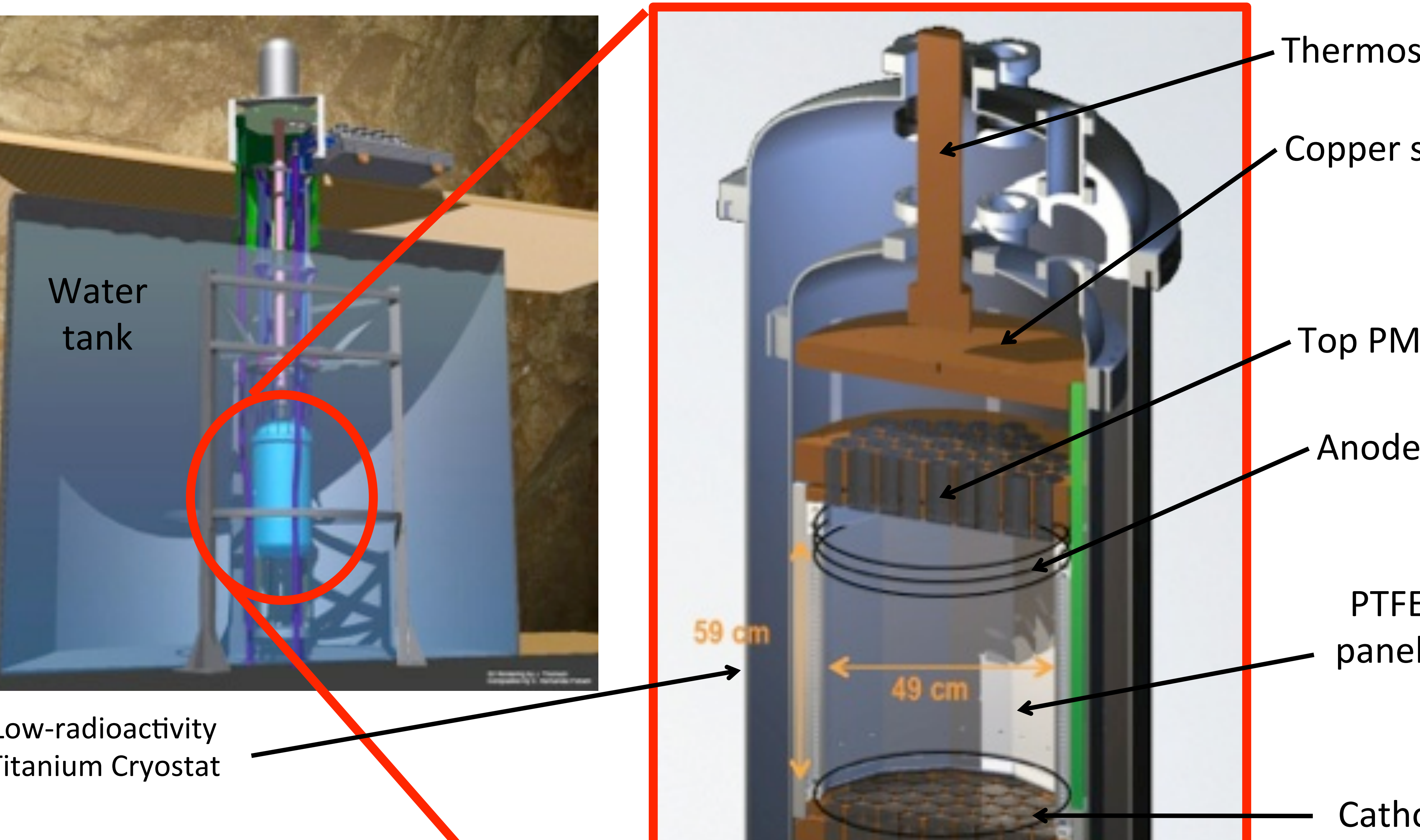
nematics alone provides strong rejectio

shielding
hat makes
X work

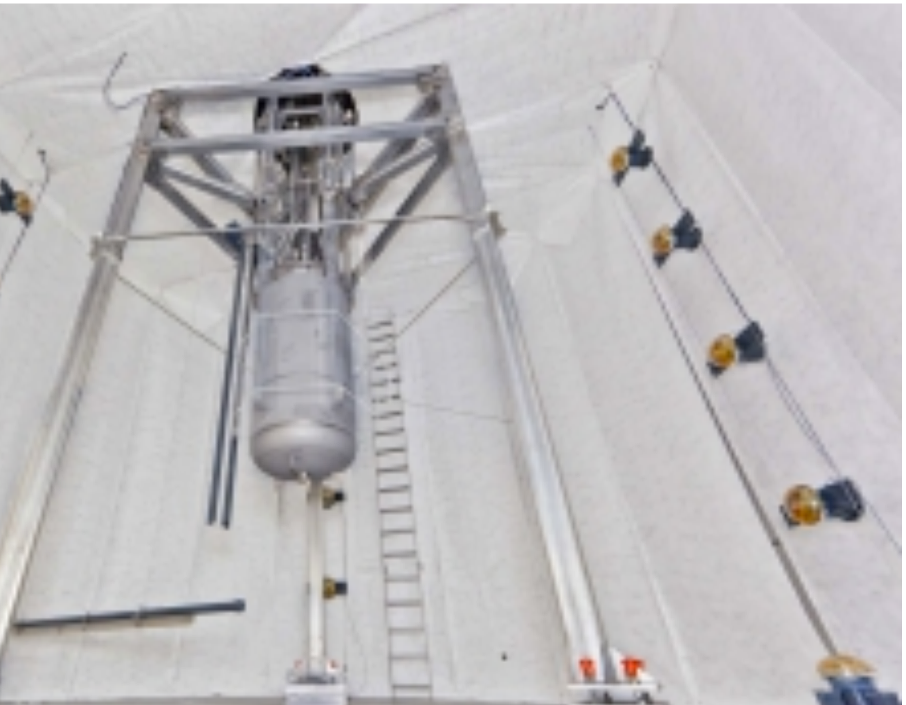
keV
osition

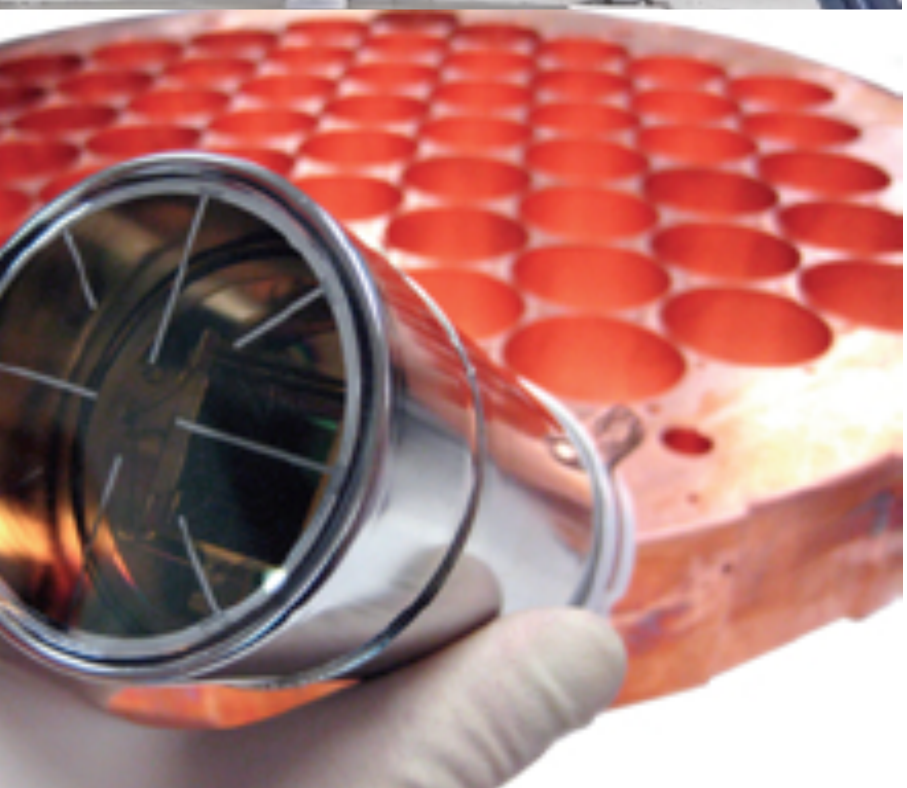


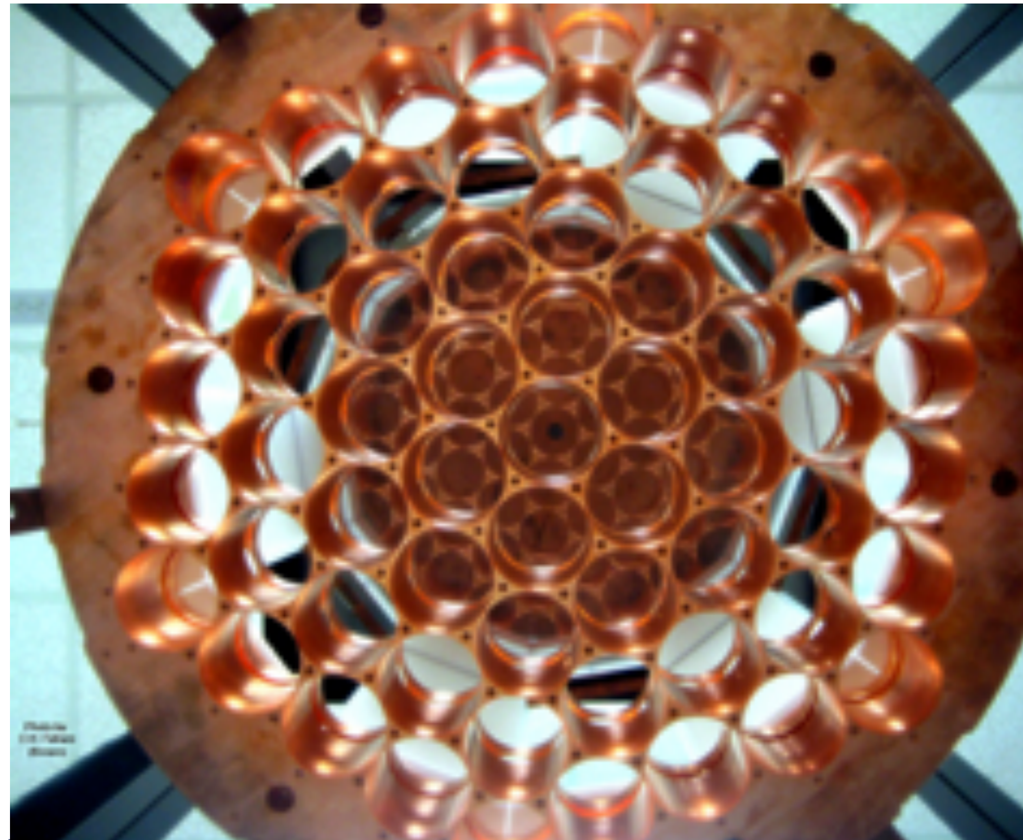
Mus
full v
wit
inter
ag

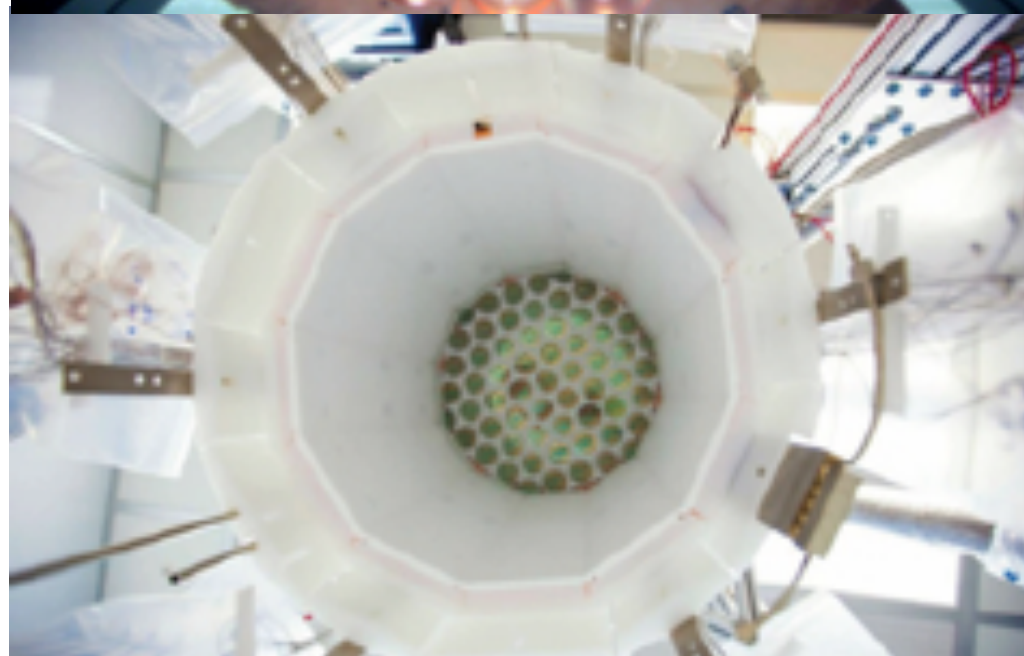


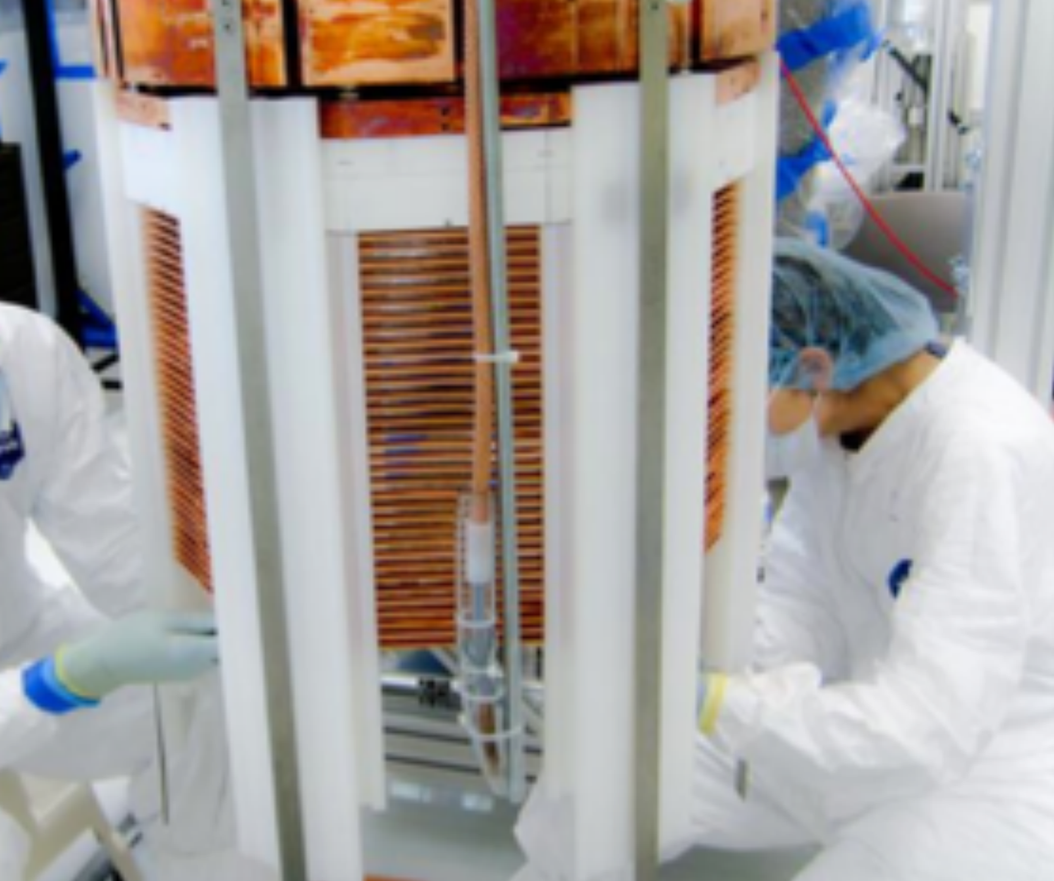
g total xenon mass
g active liquid xenon
g fiducial mass







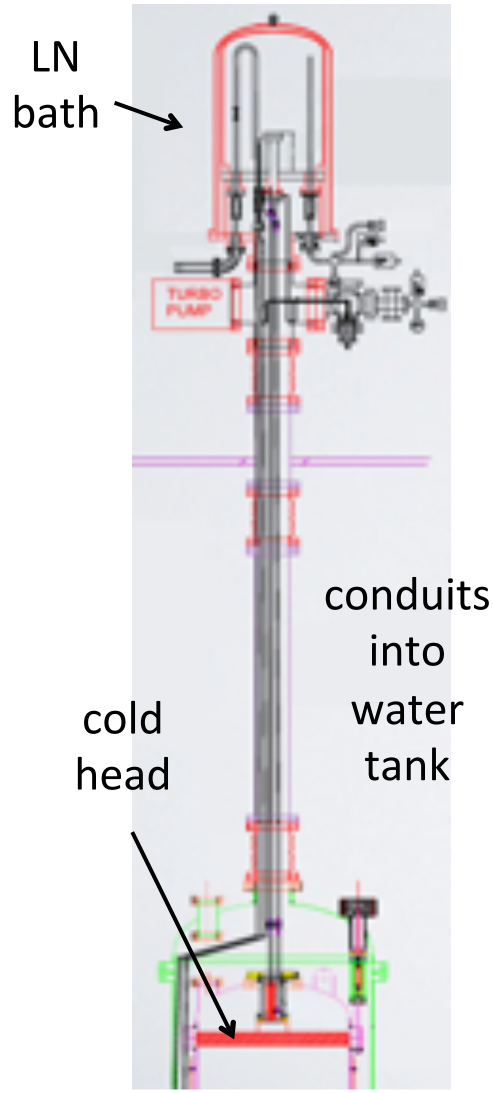




n gas handling and sampling

thode HV feedthrough

Thermosyphon cryogenics



LUX Thermosyphon

Xe storage and r

Old Homestake Mine (Hearst)
Now SURF (Sanford Underground Research Facility)
4850' underground

unded in 2008 by DOE and NSF

-ground laboratory completed at SURF in 2011
JX assembled; above-ground commissioning runs completed

ground laboratory completed at SURF in 2012.
JX moves underground in July to its new home in the Davis caver

tor cooldown and gas phase testing completed early February 20

condensation completed mid February 2013

tor commissioning completed April 2013

(3-month) WIMP search. First results presented October 2013!

ear-long WIMP search began in 2014. Result in 2016.

n Purity: electron drift length 87 –
m during Run 3

culation at 250 kg / day

onitored weekly using ^{83m}Kr data

collection efficiency: 14%

l. geometry and PMT QE

Kr data provides 3D corrections

ield: 181 V/cm

ft speed 1.51 ± 0.01 mm / ms

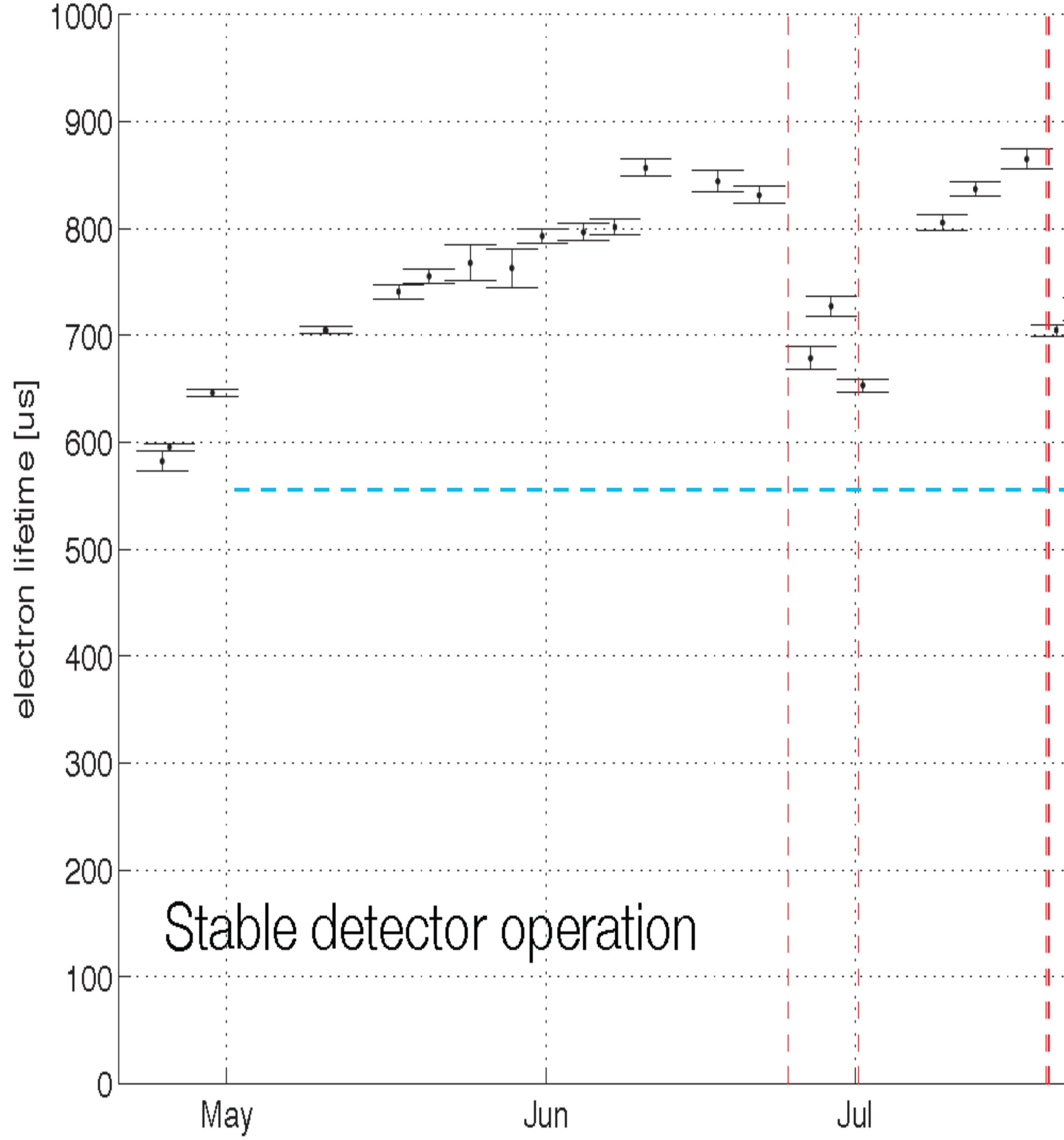
discrimination 99.6%

on extraction efficiency: 64%

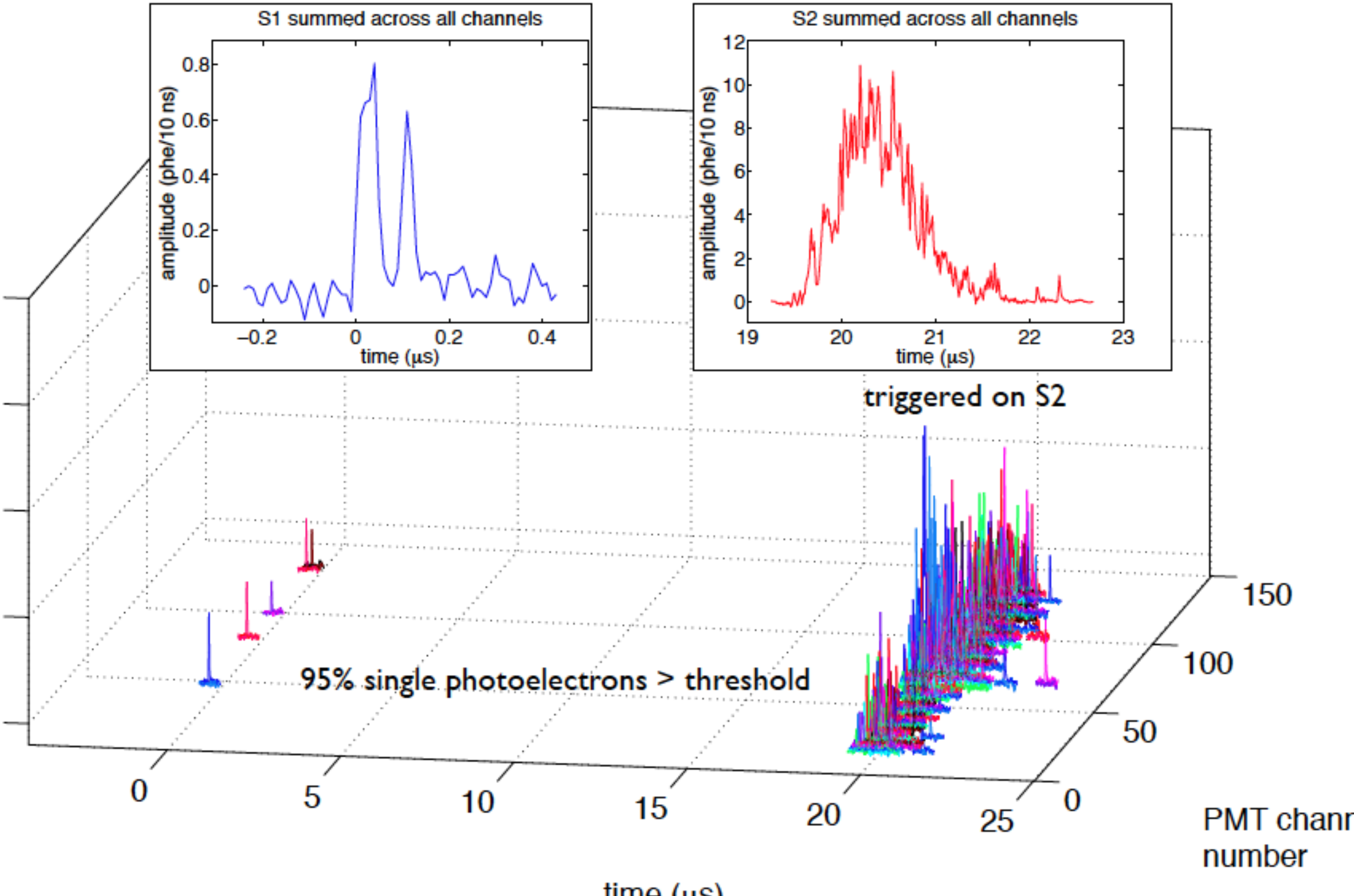
ial mass: 118.3 ± 6.5 kg

fined by background from edges

easured with homogeneous ER
ibration data... ^{83m}Kr, again!



1.5 keV gamma ray scattering event

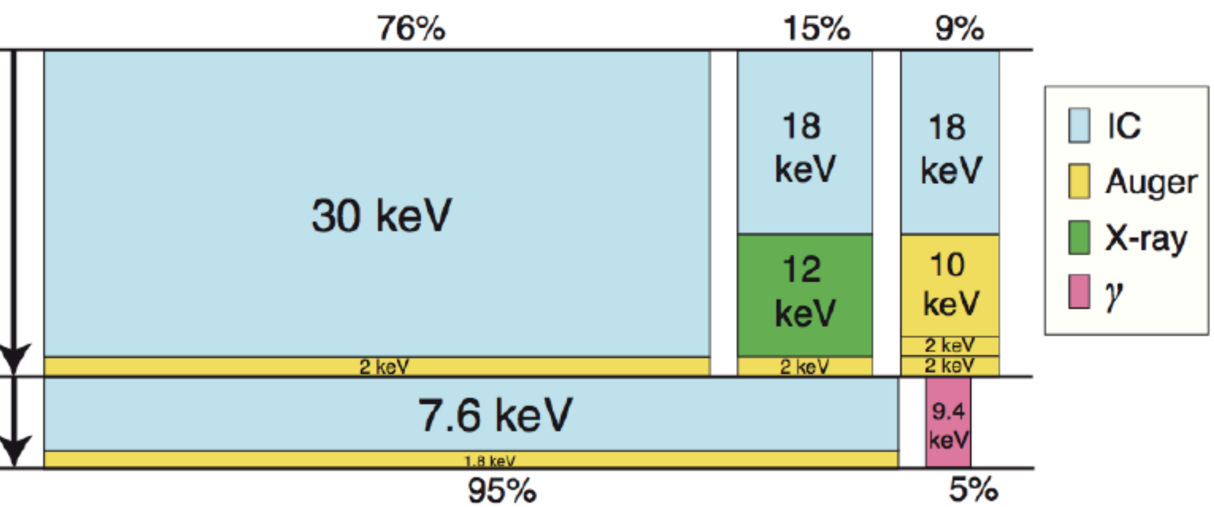


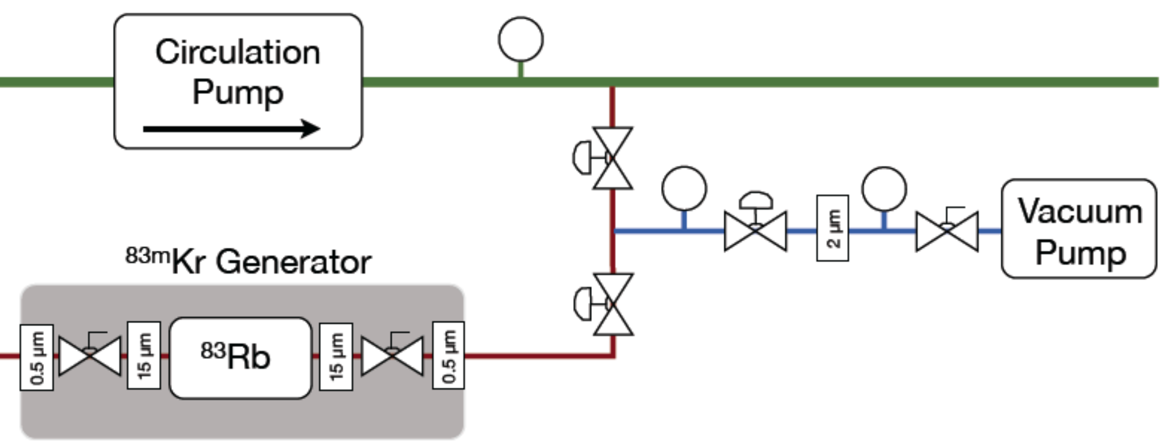
-83 produces Kr-83m when it decays; this krypton gas can then be flushed into th
X gas system to calibrate the detector as a function of position.

ovides reliable, efficient, homogeneous calibration of both S1 and S2 signals, whic
en decays away in a few hours, restoring low-background operation.

st used in liquid nobles by the McKinsey group:

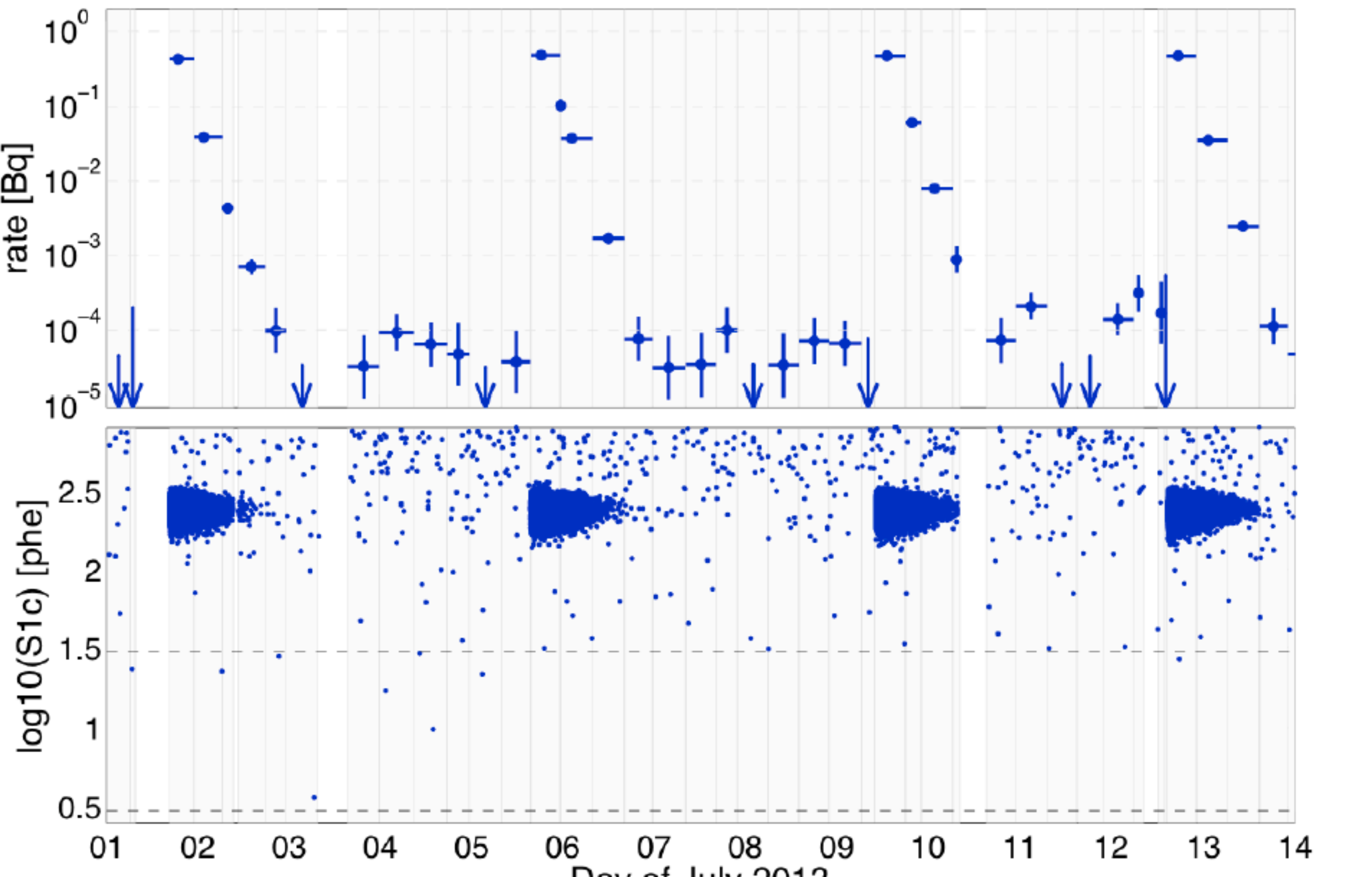
see L. Kastens et al, Phys. Rev. C **80**, 045809 (2009) and Journal of Instrumentation **5**, P05006 (20





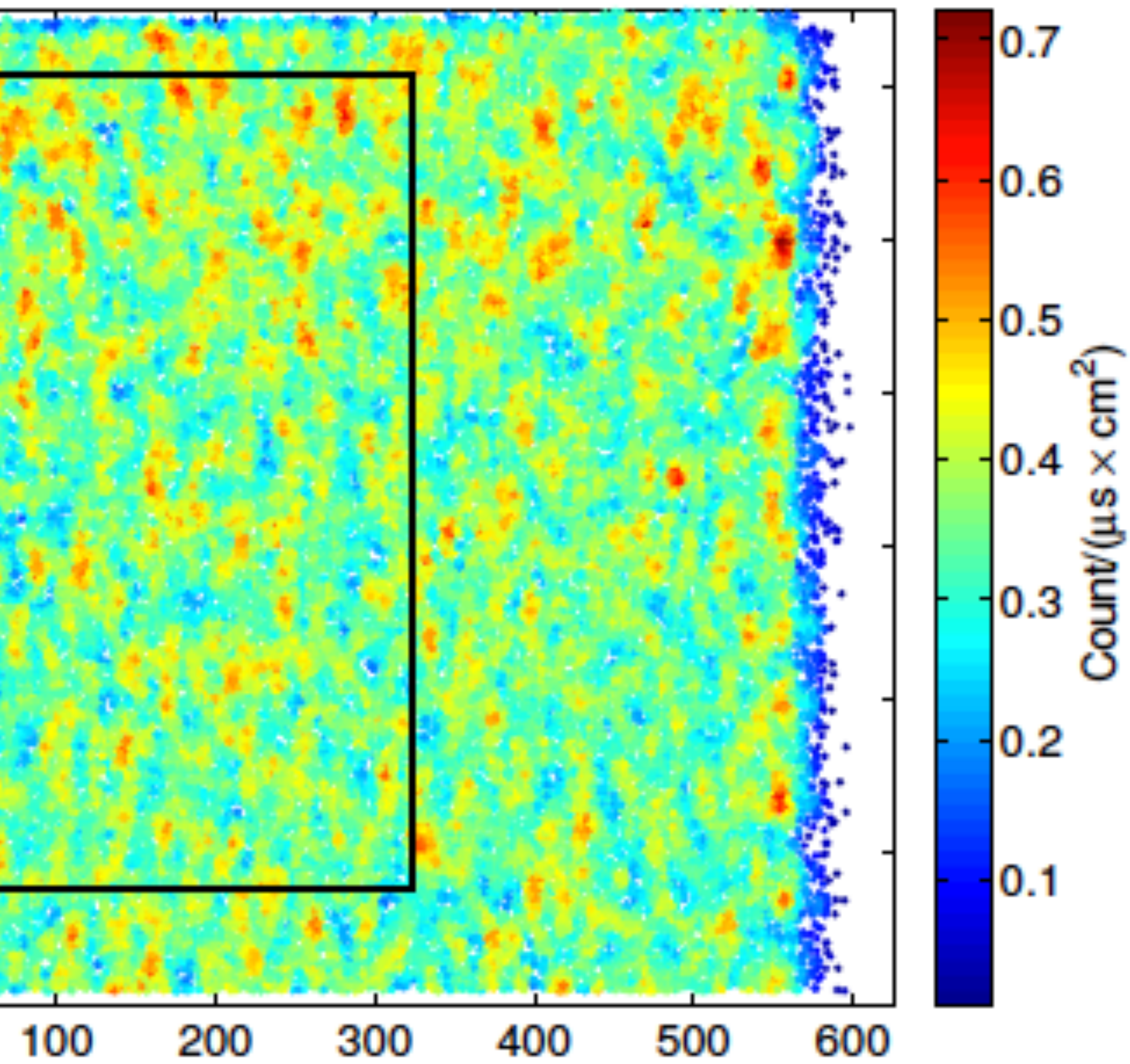
Kr-83m source (Rb-83 coated on
charcoal, within xenon gas plum

Repeated, frequent use of Kr-83m

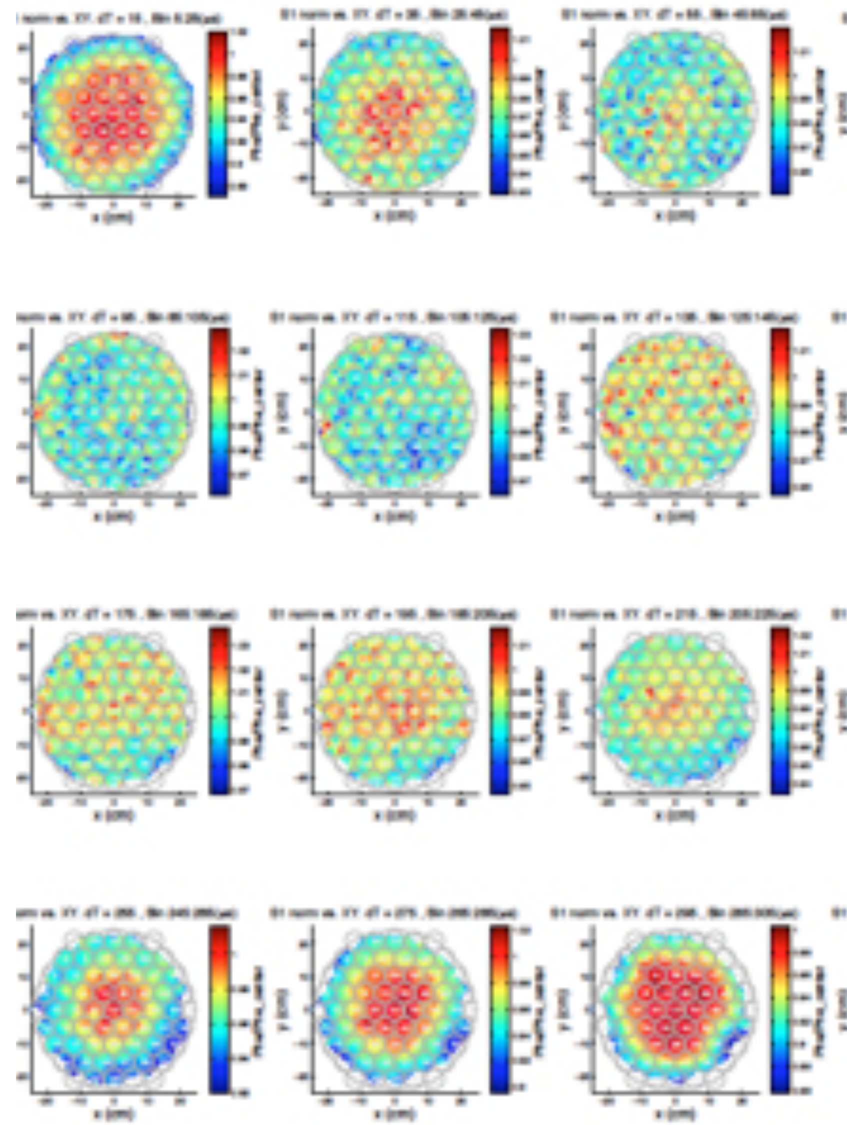


1 million Kr-83m events, spread uniformly through the detect

lucial volume determination



Position-based S1 correc

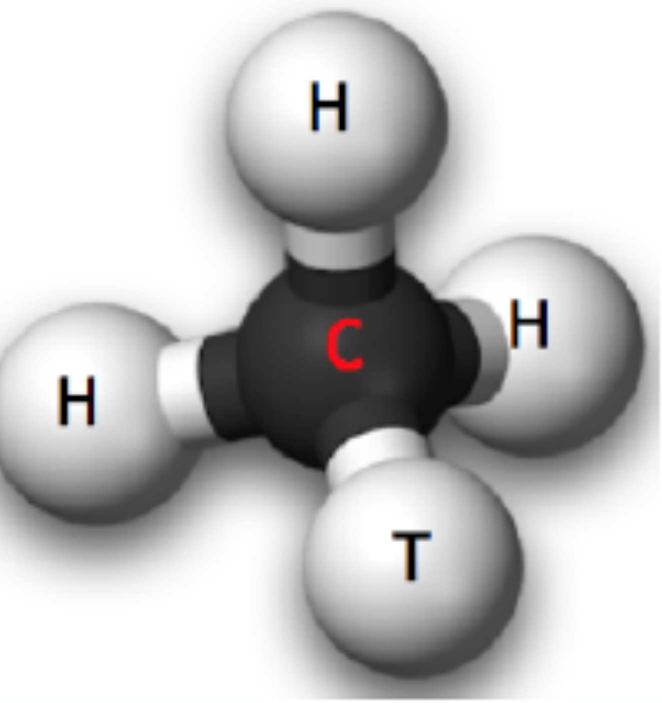


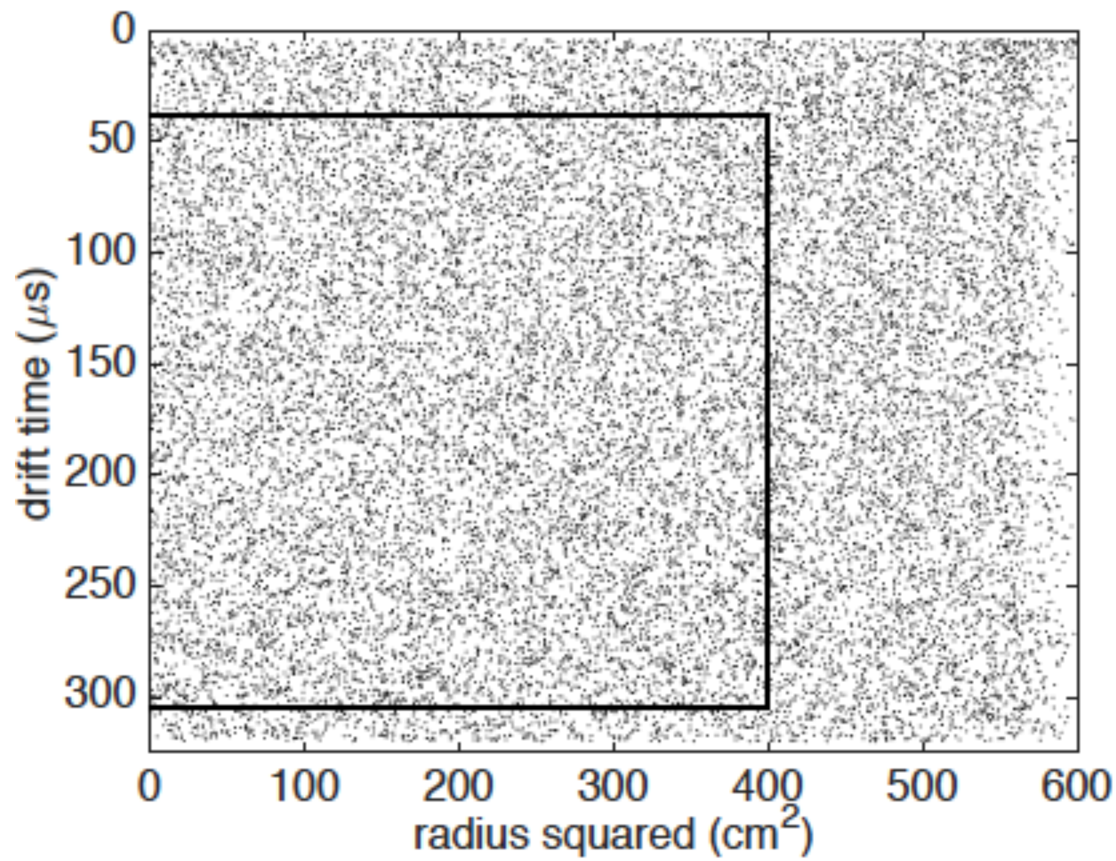
X uses tritiated methane, doped into the detector, to accurately calibrate the effici
ackground rejection.

s beta source (endpoint energy 18 keV) allows electron recoil S2/S1 band calibratio
n unprecedented accuracy

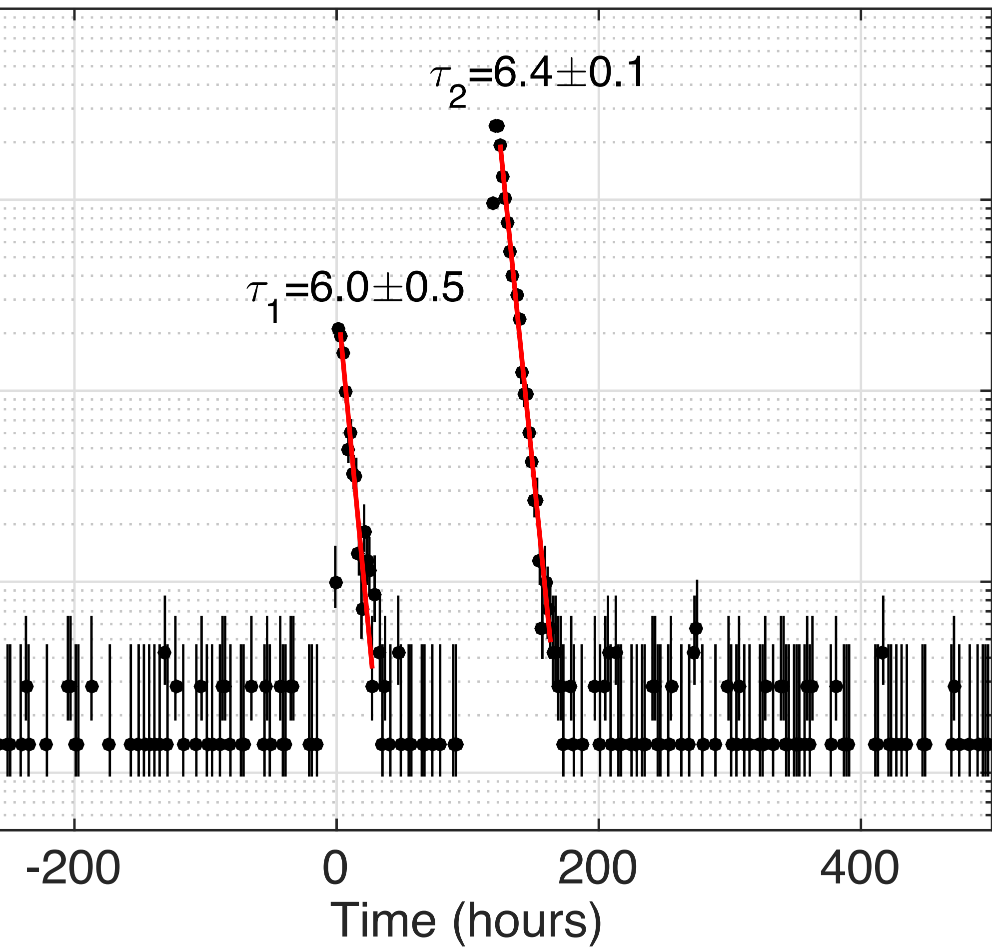
tritiated methane is then fully removed by circulating the xenon through the gett

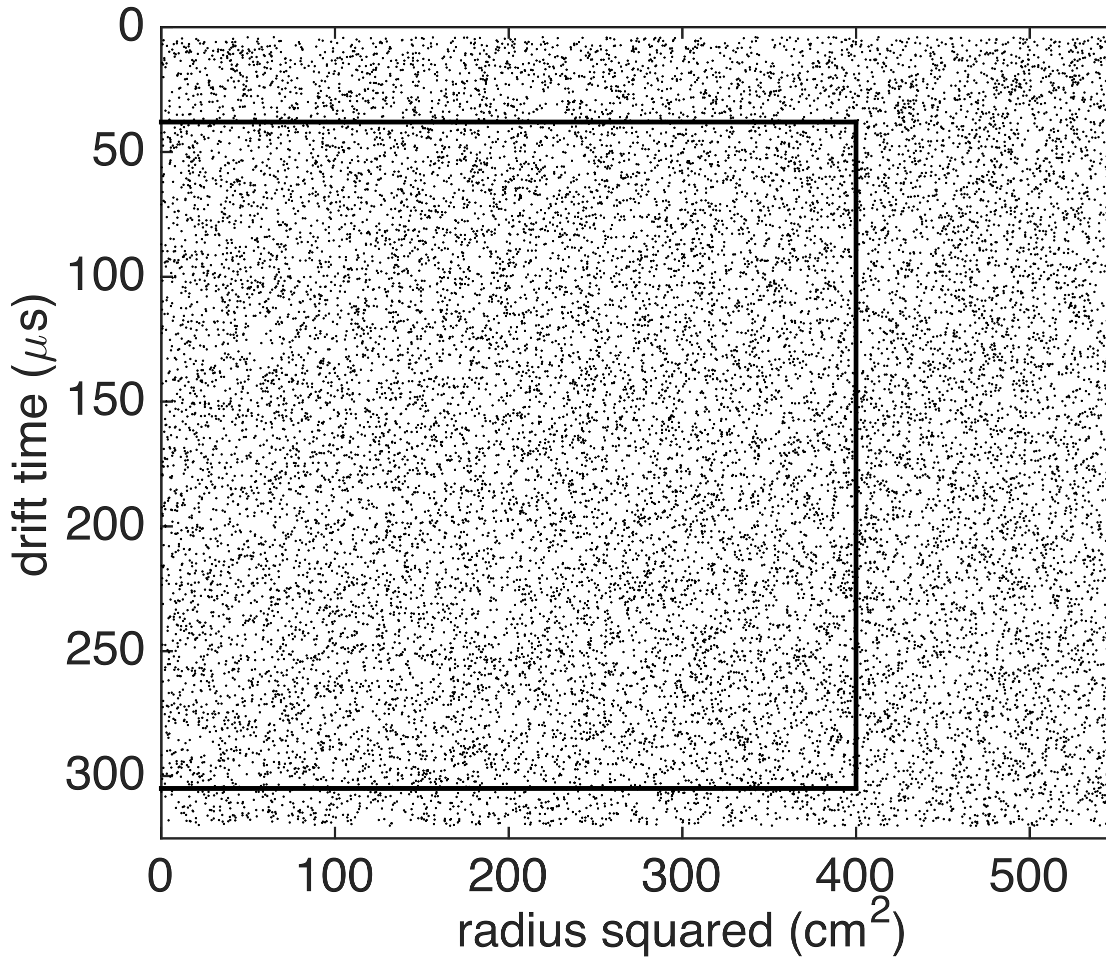
ametrization of the electron recoil band from the high-statistics tritiated methane
n is then used to characterize the background model.



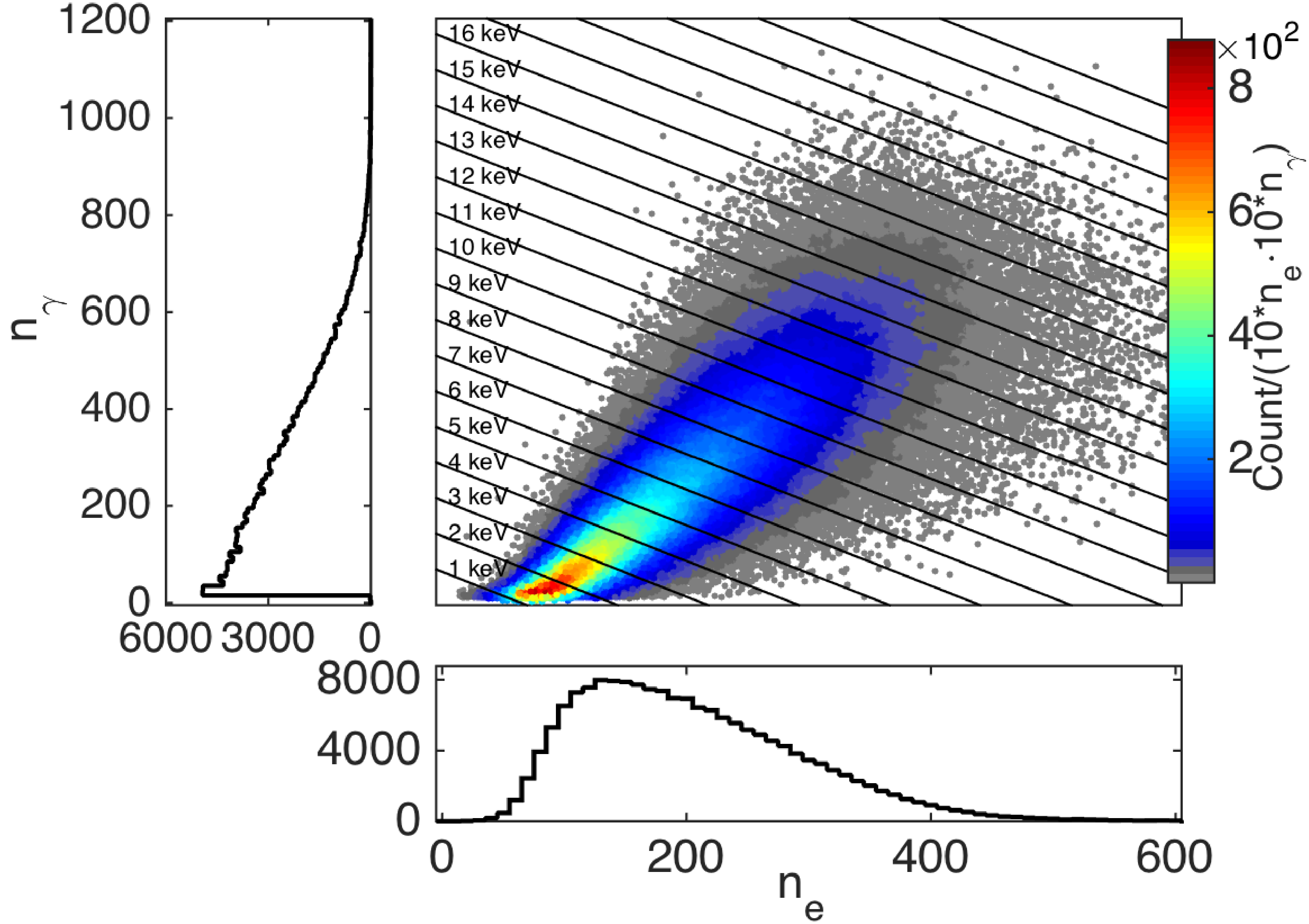


Tritiated Methane injection



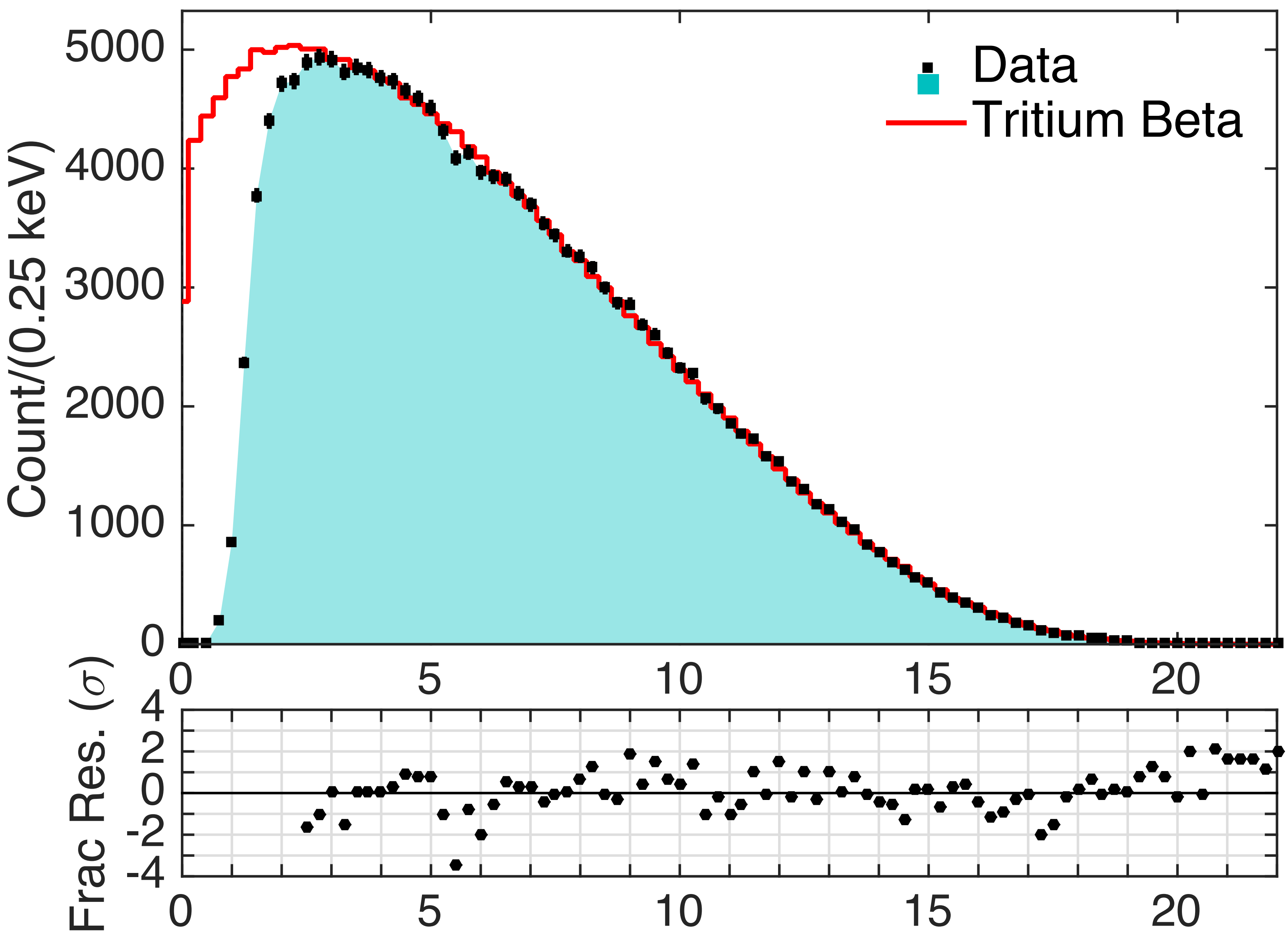


Tritium beta decay measured in both light and charge

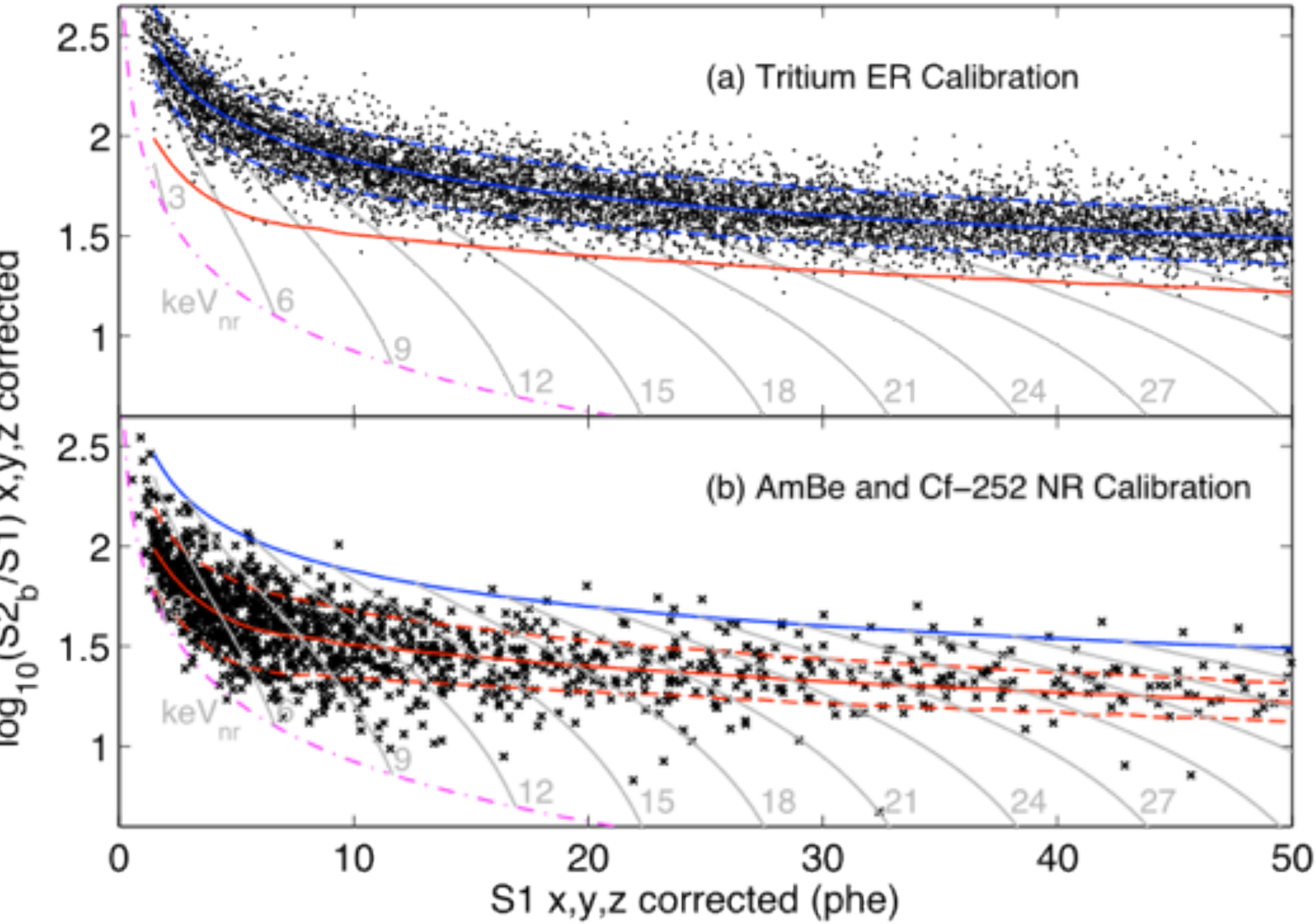


Tritium combined energy spectrum

$$\mathrm{E} = \mathrm{W}(\mathrm{n}_\gamma + \mathrm{n}_\mathrm{e}) = \mathrm{W}\left(\frac{\mathrm{S1}}{\mathrm{g}_1} + \frac{\mathrm{S2}}{\mathrm{g}_2}\right)$$



n provides very high statistics electron recoil calibration (200 even
n calibration is consistent with NEST + simulations



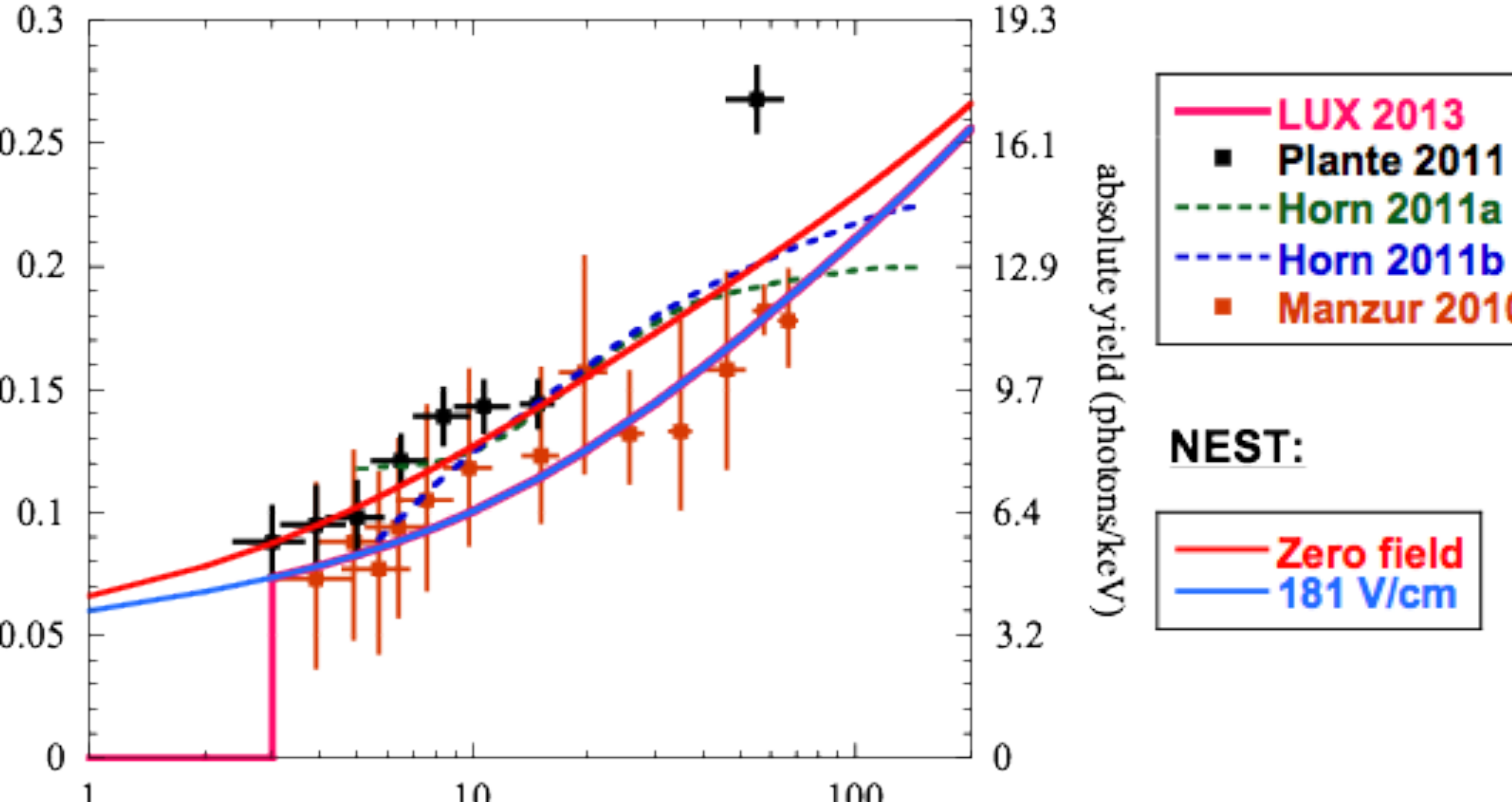
eled Using Noble Element Simulation Technique (NEST).

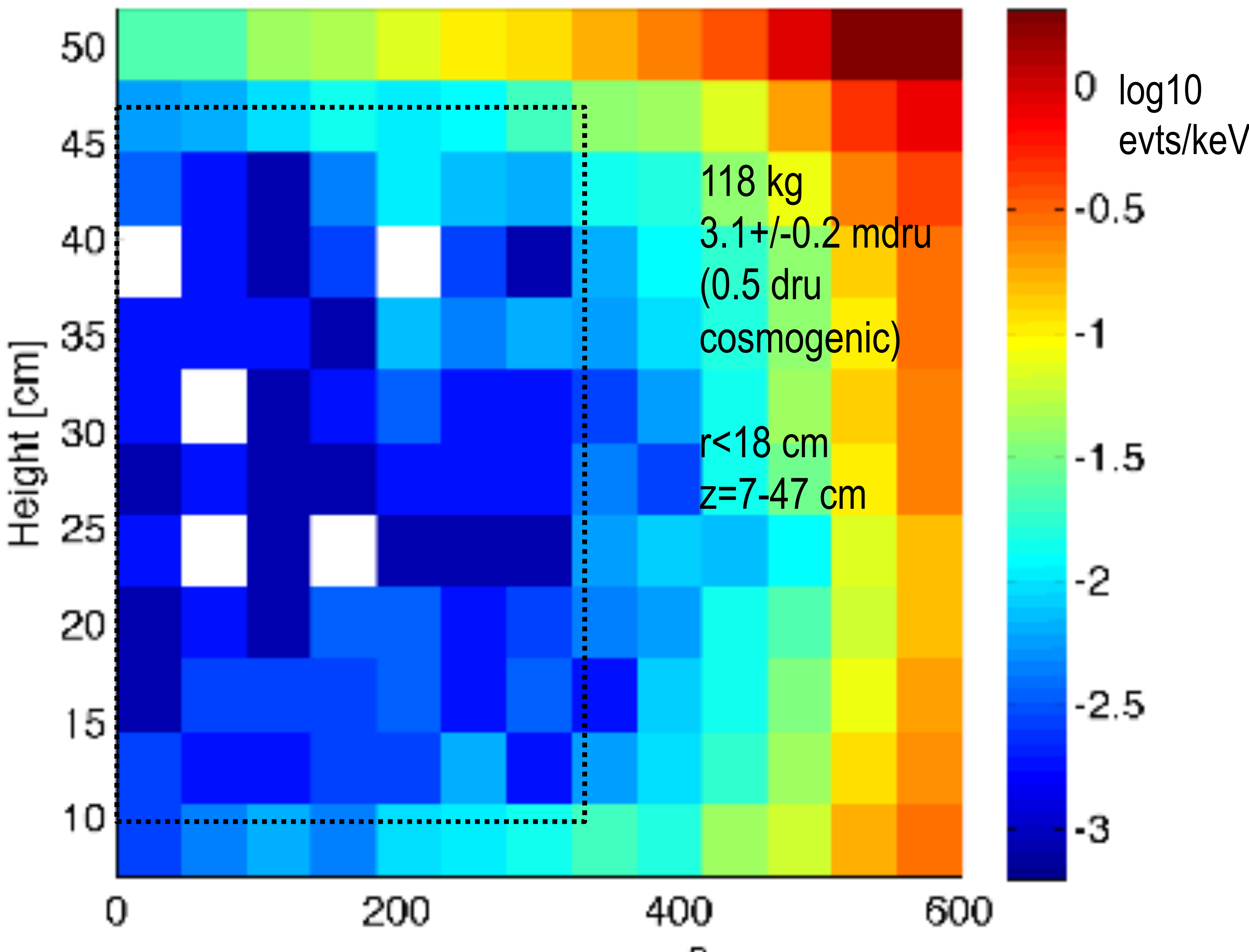
based on canon of existing experimental data.

st result, artificial cutoff in light and charge yields assumed below 3 keVnr,

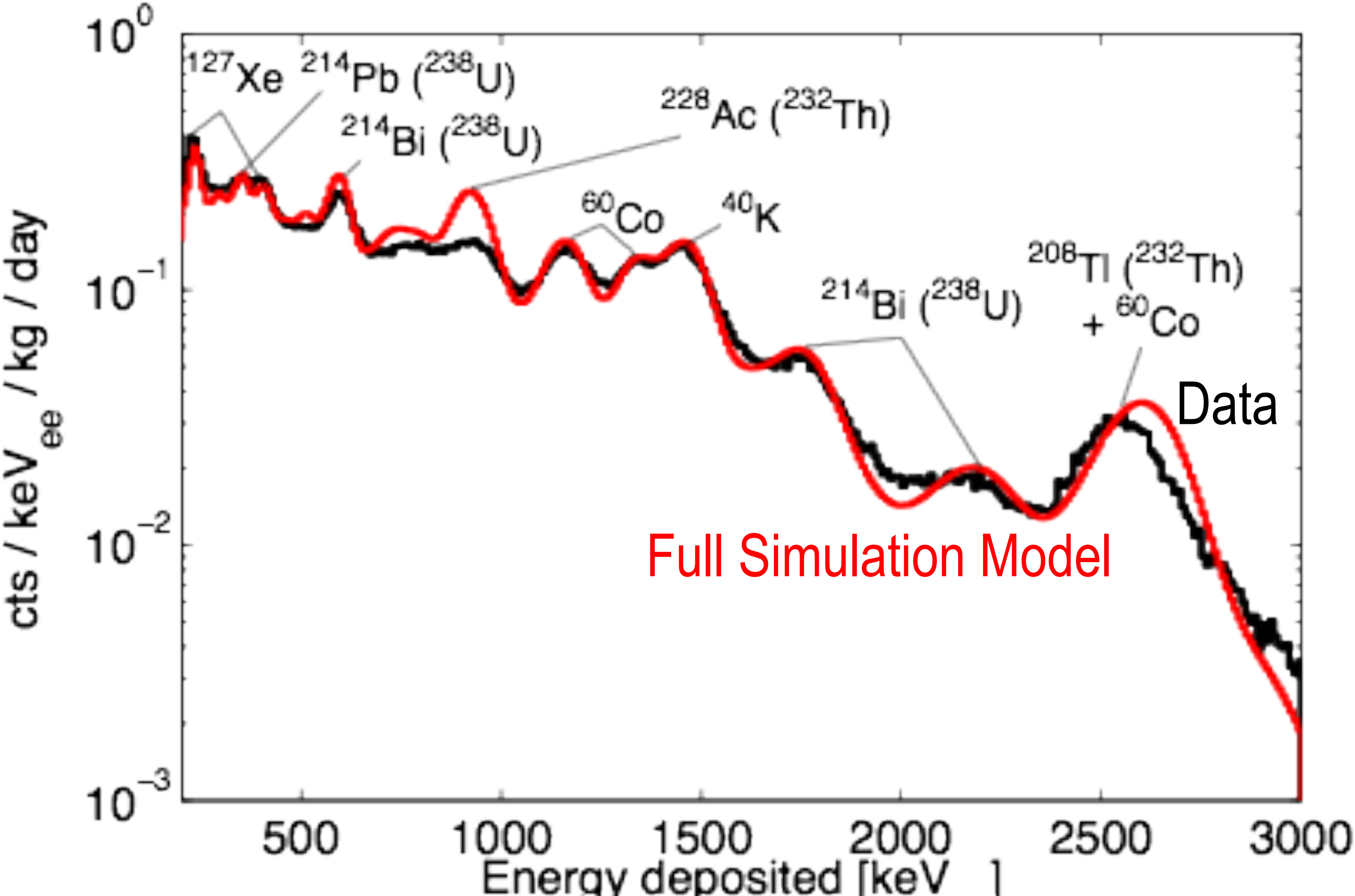
o be conservative.

des predicted electric field quenching of light signal, to 77-82% of the zero field lig




50
45
40
35
30
25
20
15
10
Height [cm]
0
200
400
600
118 kg
3.1+/-0.2 mdru
(0.5 dru
cosmogenic)
r<18 cm
z=7-47 cm
0
-0.5
-1
-1.5
-2
-2.5
-3
log10
evts/keV

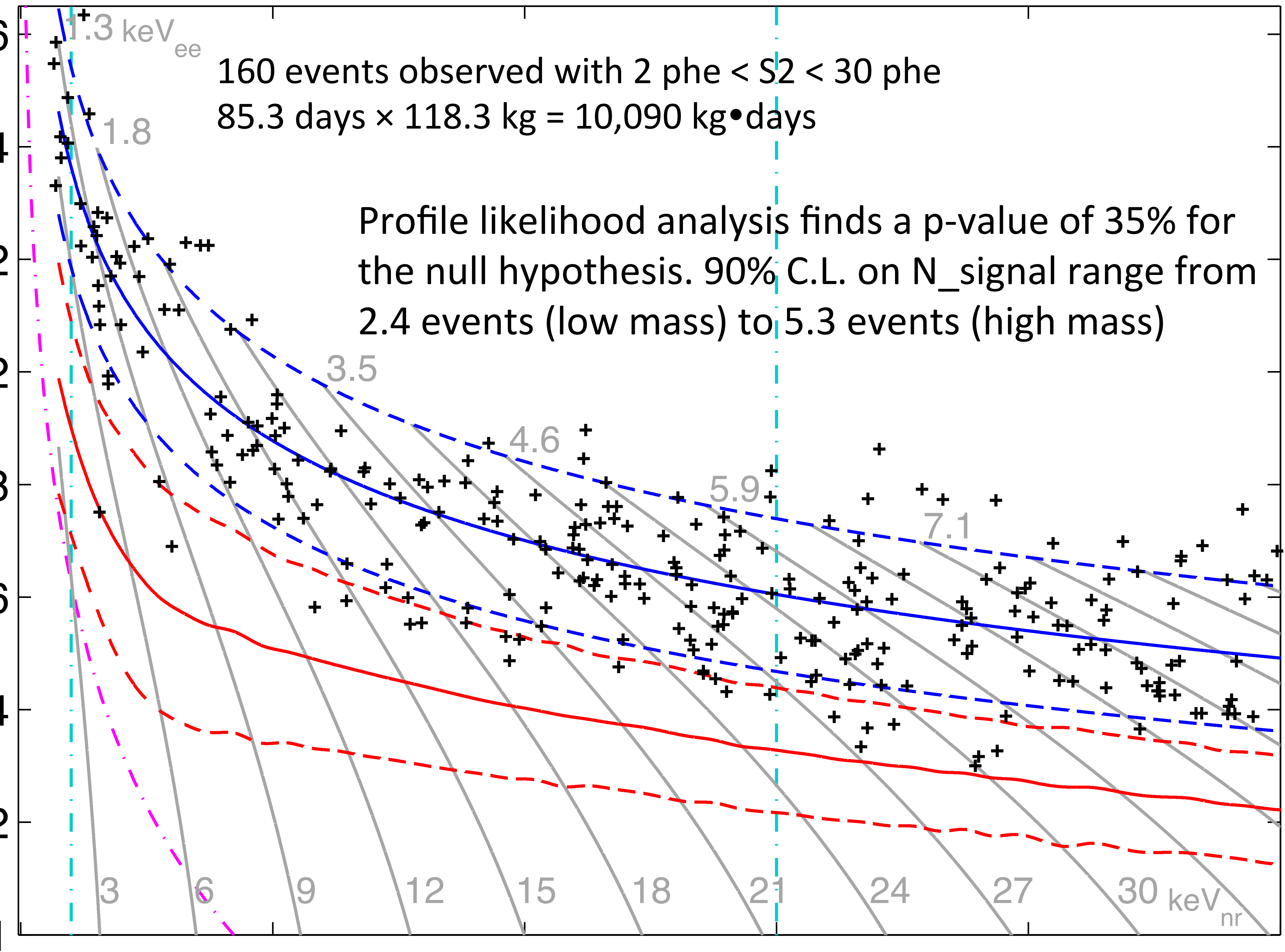
amma spectrum, excluding region ±2 cm from top/bottom gr

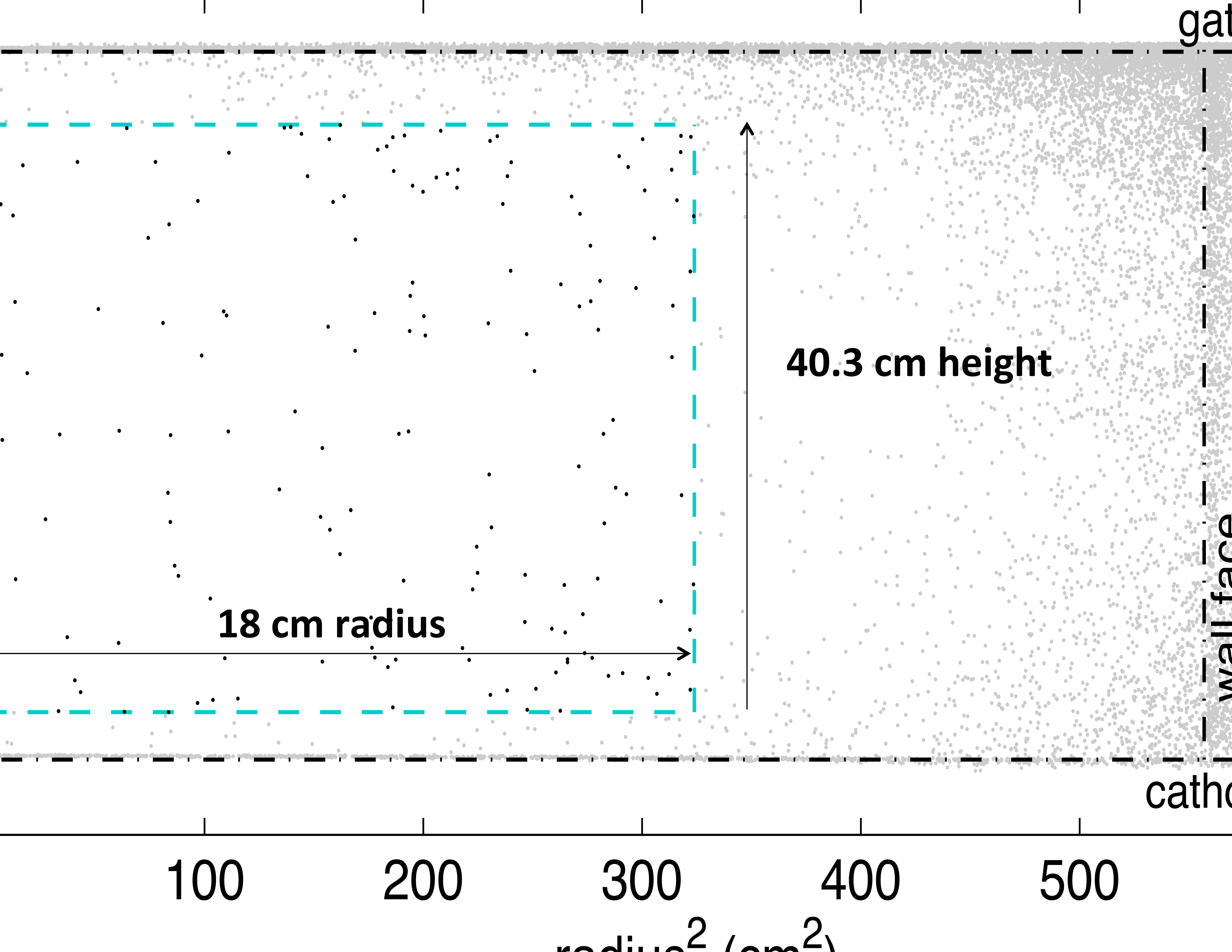


verage levels over period April-August WIMP Search Run

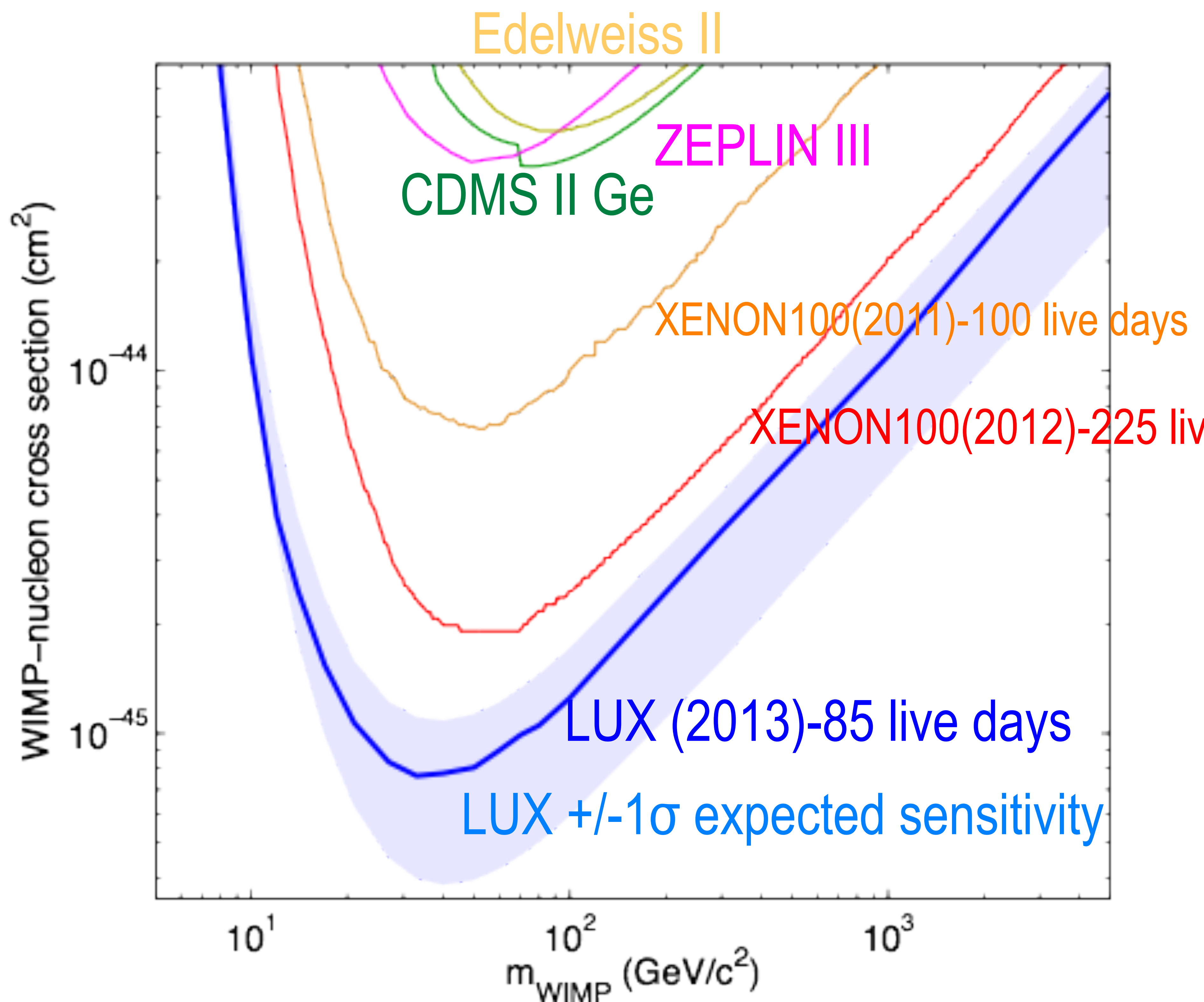
Background Component	Source	10^{-3} x evts/keVee/kg/day
Gamma-rays	Internal Components including PMTS (80%), Cryostat, Teflon	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe (36.4 day half-life)	Cosmogenic 0.87 -> 0.28 during run	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	222Rn	0.11-0.22(90% CL)
^{85}Kr	Reduced from 130 ppb to 3.5±1 ppt	$0.13 \pm 0.07_{sys}$
Predicted	Total	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Observed	Total	$3.1 \pm 0.2_{stat}$

	Explanation	Events Remaining
ggers	S2 Trigger >99% for $S2_{raw}$>200 phe	83,673
tor Stability	Cut periods of excursion for Xe Gas Pressure, Xe Liquid Level, Grid Voltages	82,918
Scatter Events	Identification of S1 and S2. Single Scatter cut.	6,585
ergy	Accept 2-30 phe (energy ~ 0.9-5.3 keVee, ~3-25 keVnr)	26
ergy	Accept 200-3300 phe (>8 extracted electrons) Removes single electron / small S2 edge events	20
gle Electron Quiet Cut	Cut if >100 phe outside S1+S2 identified +/-0.5 ms around trigger (0.8% drop in livetime)	19
ime Cut away from	Cutting away from cathode and gate regions, 60 < drift time < 324 us	8
l Volume radius and drift	Radius < 18 cm, 38 < drift time < 305 us,	

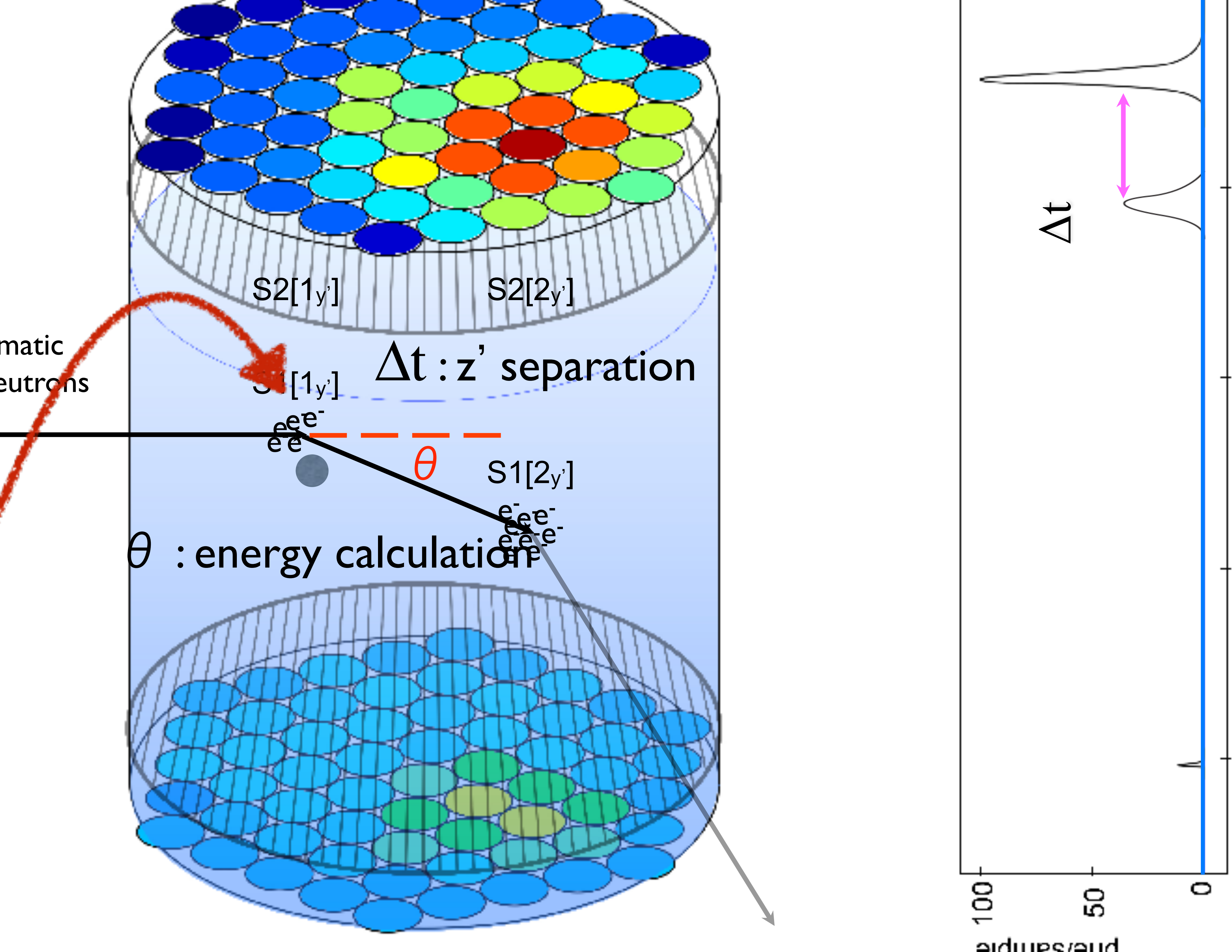

1.3 keV$_{ee}$
1.8
3.5
4.6
5.9
7.1
160 events observed with 2 phe < S2 < 30 phe
85.3 days × 118.3 kg = 10,090 kg•days
Profile likelihood analysis finds a p-value of 35% for the null hypothesis. 90% C.L. on N_signal range from 2.4 events (low mass) to 5.3 events (high mass)
3
6
9
12
15
18
21
24
27
30 keV$_{nr}$



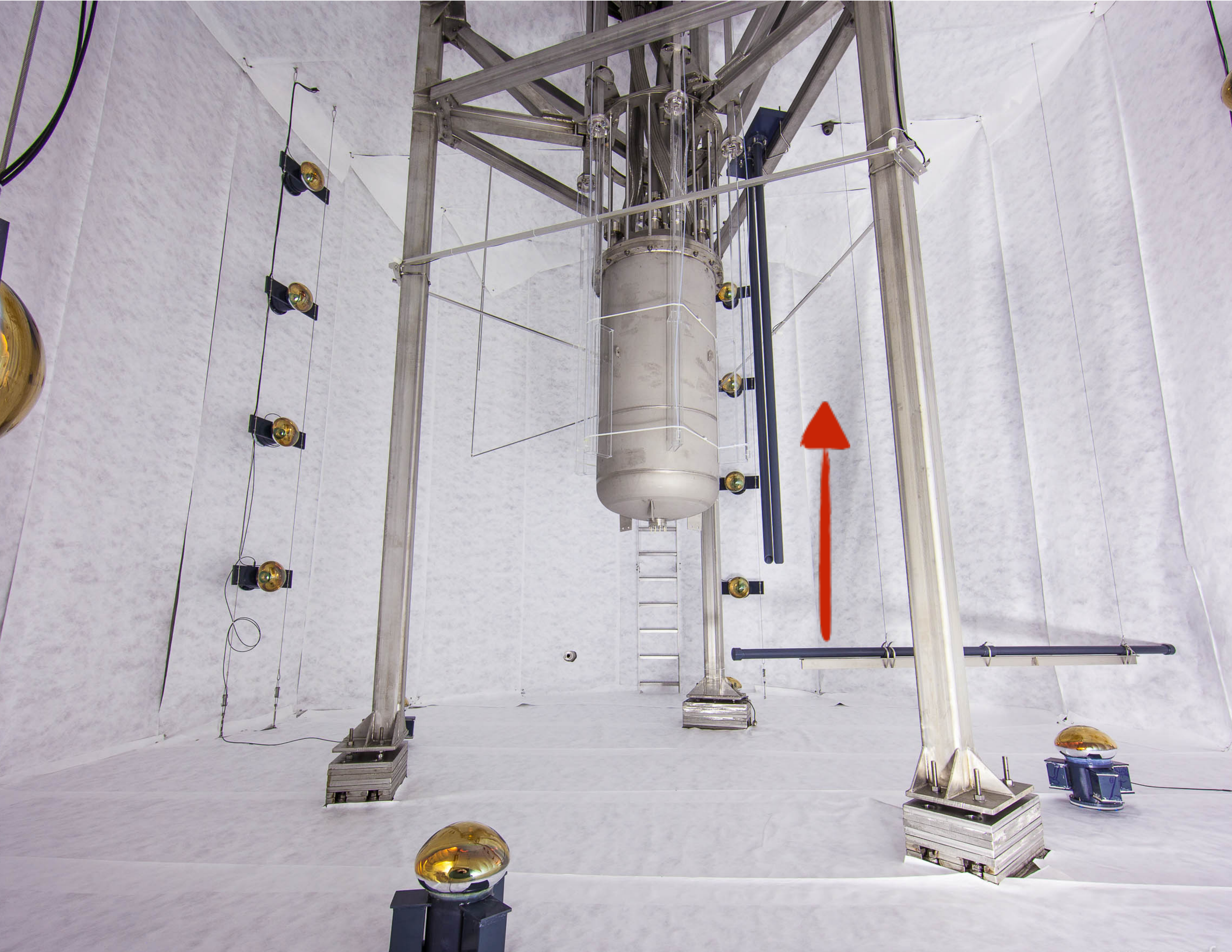
gat
40.3 cm height
18 cm radius
wall face
catho
100
200
300
400
500
radius^2 (cm^2)

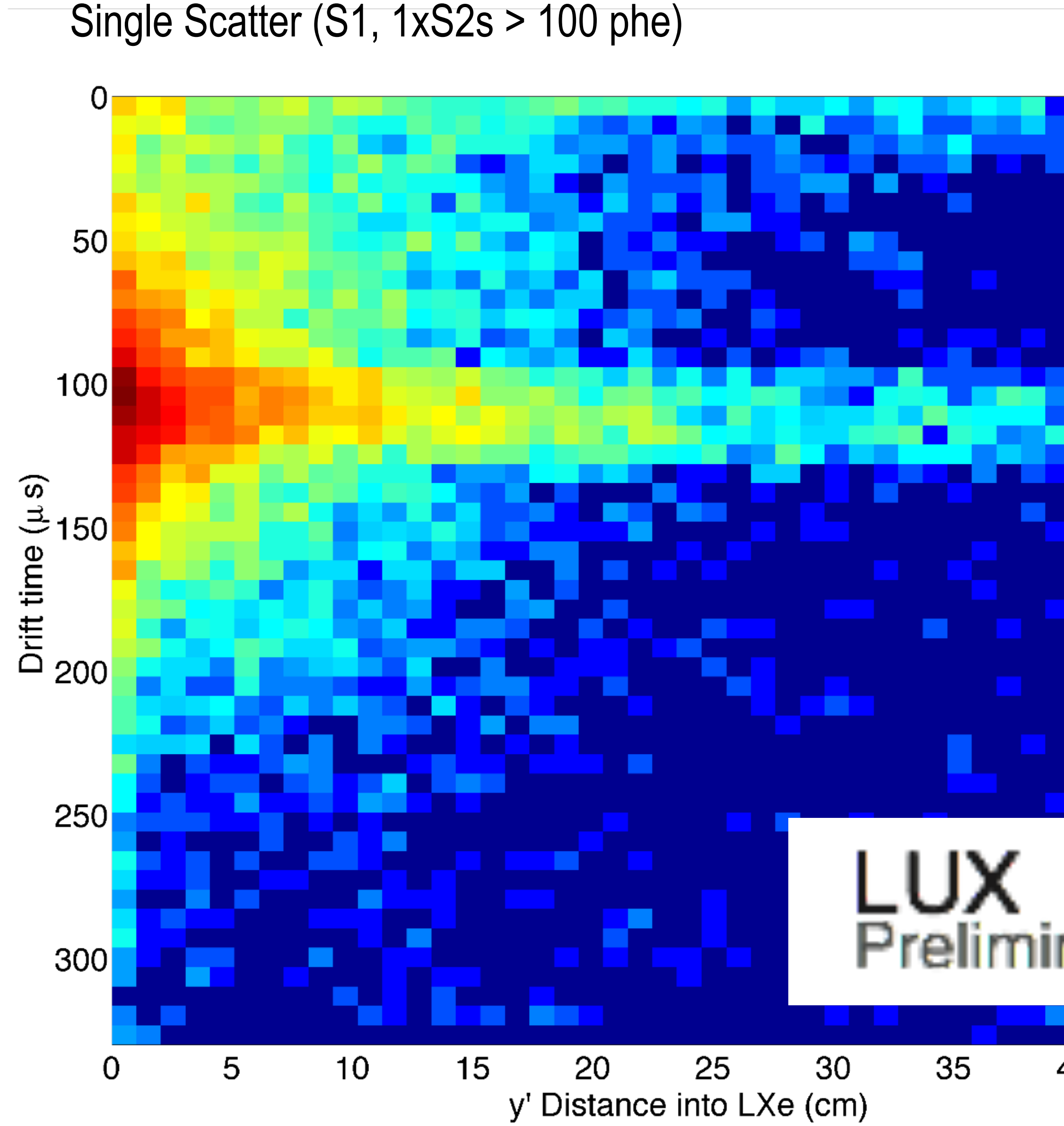


Edelweiss II
ZEPLIN III
CDMS II Ge
XENON100(2011)-100 live days
XENON100(2012)-225 liv
LUX (2013)-85 live days
LUX +/-1σ expected sensitivity
WIMP–nucleon cross section (cm^2)
10^{-44}
10^{-45}
10^1
10^2
10^3
m_{WIMP} (GeV/c^2)



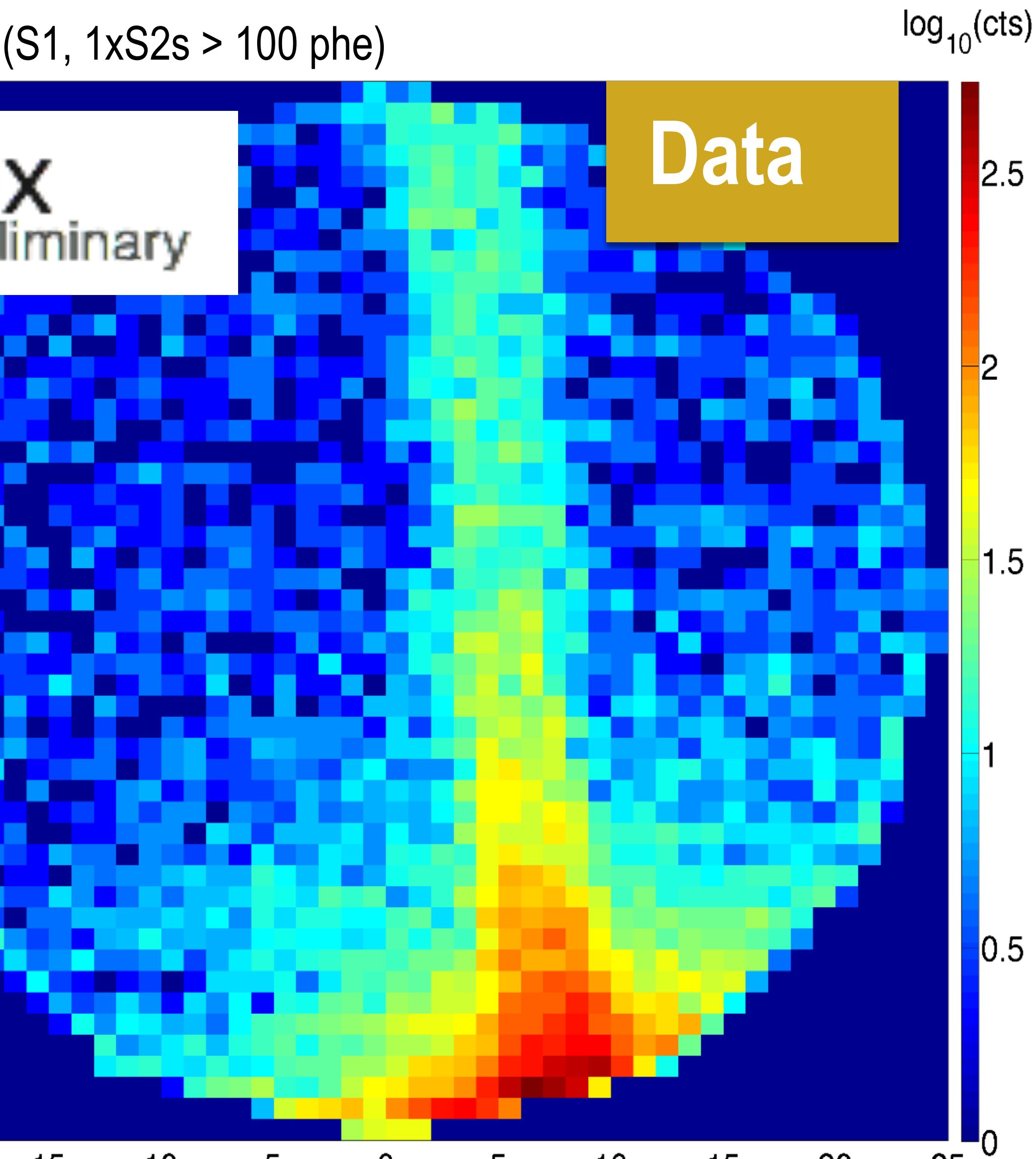
matic
eutrons
S2[1y']
S2[2y']
Δt : z' separation
S1[1y']
θ
S1[2y']
θ : energy calculation
Δt
100
50
0

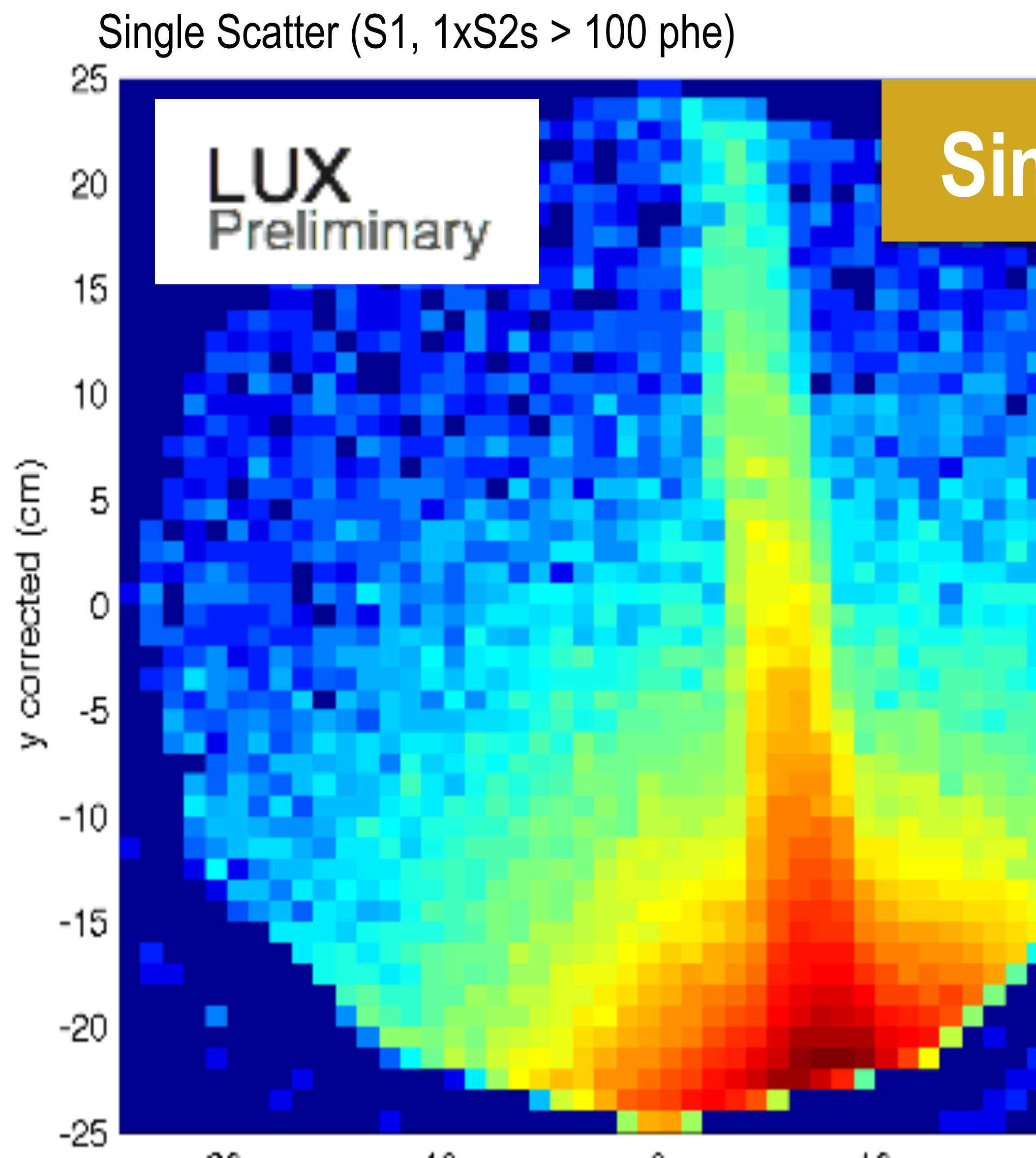


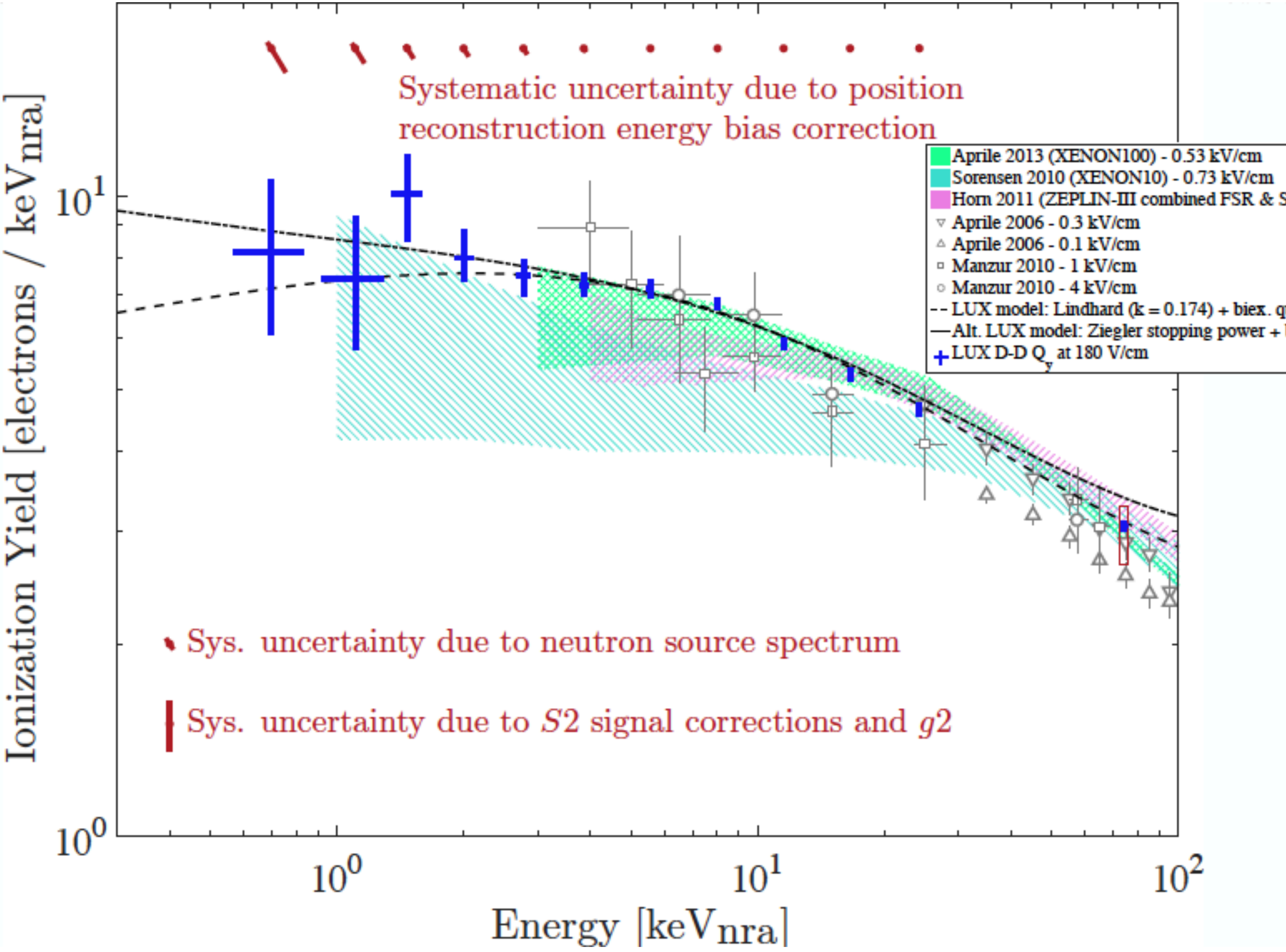


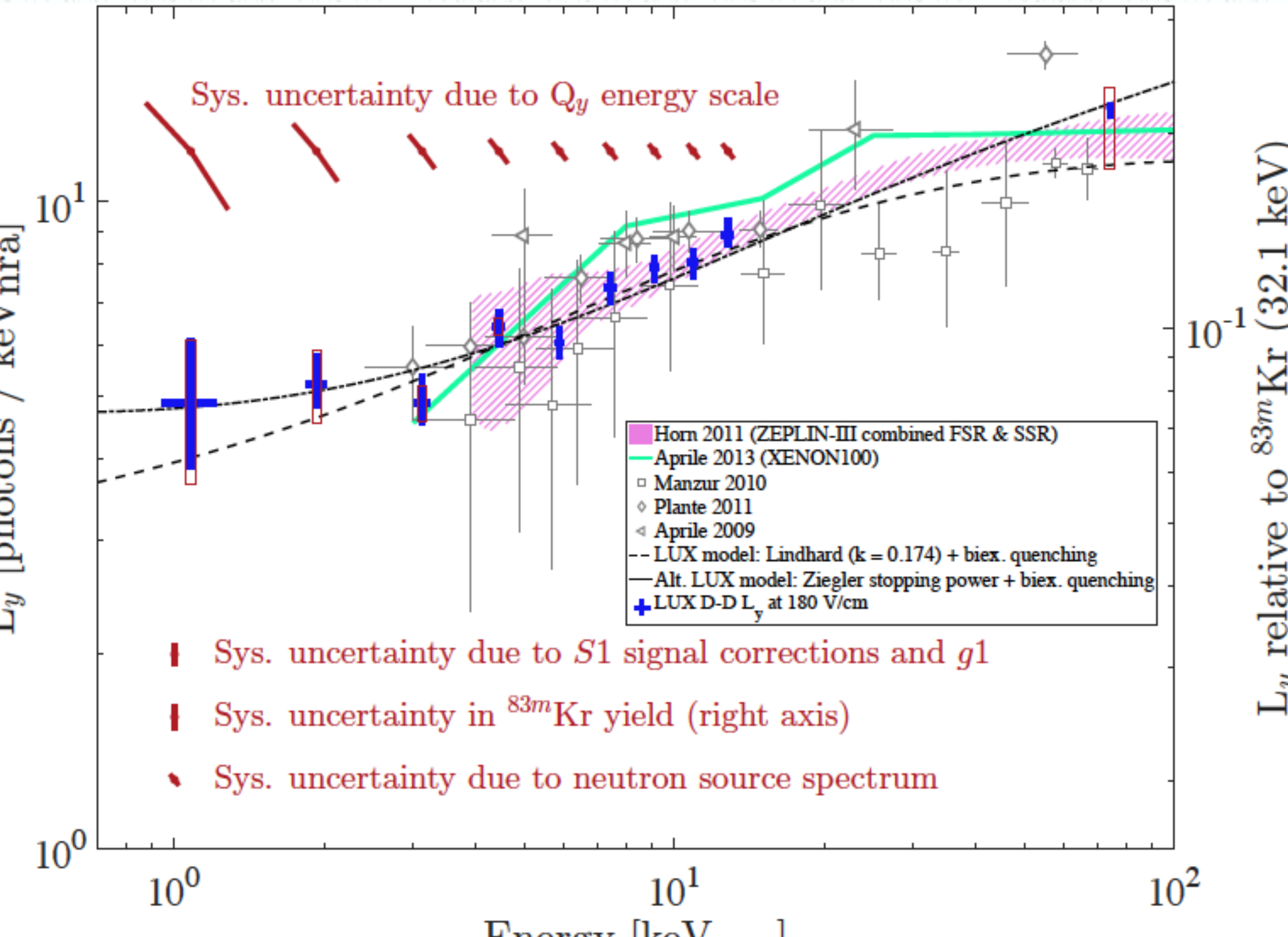
- Neutron generator/beam pipe assembly a
15.5 cm below liquid level in LUX active re
maximize usable single / double scatters
- Beam leveled to ~1 degree
- 105.5 live hours of neutron tube data use

Complete Geant4 LUXSim + NEST simulation of D-D neutron calibration






Systematic uncertainty due to position
reconstruction energy bias correction
Aprile 2013 (XENON100) - 0.53 kV/cm
Sorensen 2010 (XENON10) - 0.73 kV/cm
Horn 2011 (ZEPLIN-III combined FSR & S
Aprile 2006 - 0.3 kV/cm
Aprile 2006 - 0.1 kV/cm
Manzur 2010 - 1 kV/cm
Manzur 2010 - 4 kV/cm
LUX model: Lindhard (k = 0.174) + biex. q
Alt. LUX model: Ziegler stopping power +
LUX D-D Q_y at 180 V/cm
Sys. uncertainty due to neutron source spectrum
Sys. uncertainty due to S2 signal corrections and g2
Ionization Yield [electrons / keV_nra]
Energy [keV_nra]
10^1
10^0
10^0
10^1
10^2

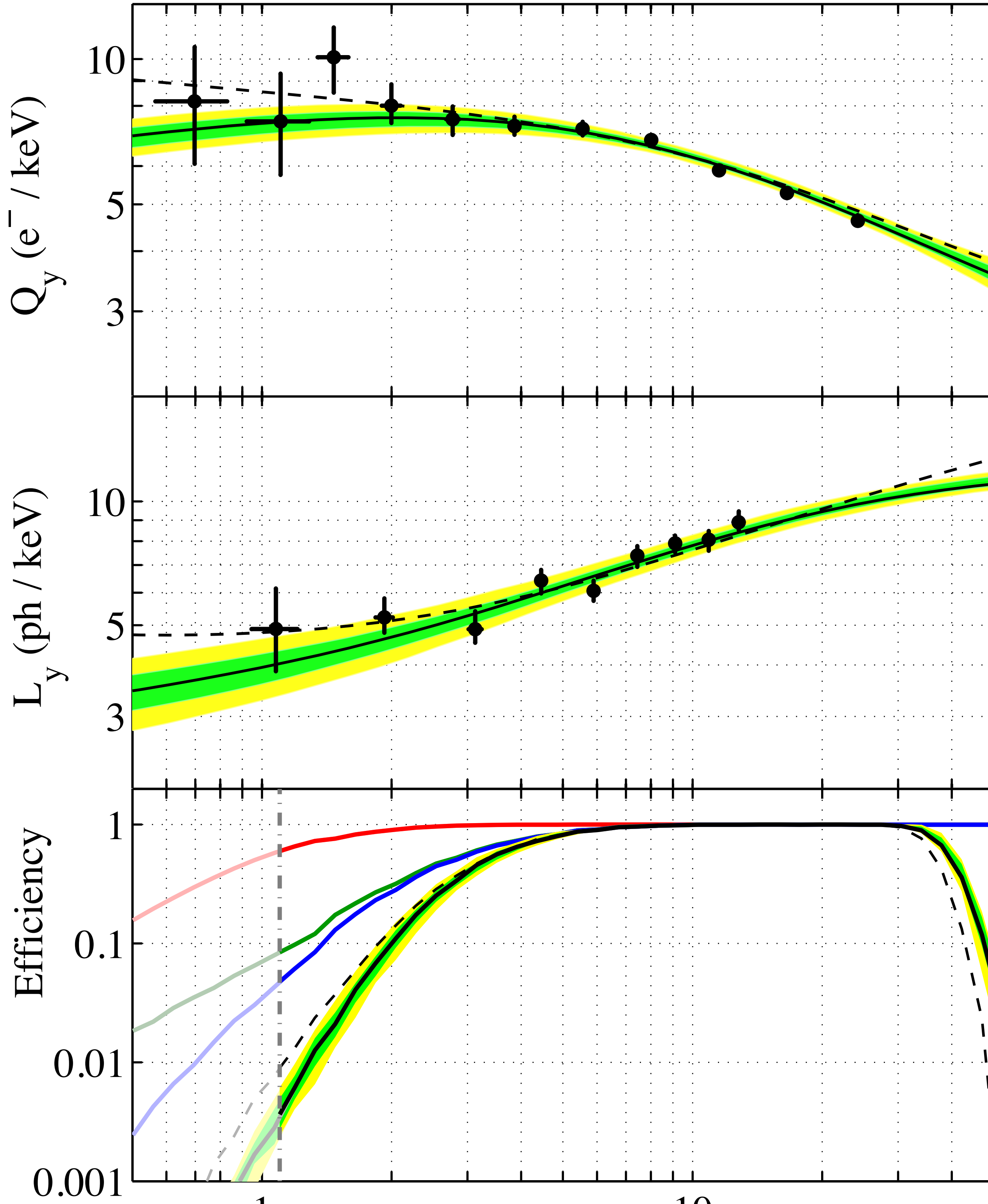


Sys. uncertainty due to Q_y energy scale
Horn 2011 (ZEPLIN-III combined FSR & SSR)
Aprile 2013 (XENON100)
Manzur 2010
Plante 2011
Aprile 2009
LUX model: Lindhard (k = 0.174) + biex. quenching
Alt. LUX model: Ziegler stopping power + biex. quenching
LUX D-D L_y at 180 V/cm
Sys. uncertainty due to $S1$ signal corrections and $g1$
Sys. uncertainty in ^{83m}Kr yield (right axis)
Sys. uncertainty due to neutron source spectrum
10^1
10^0
10^{-1}
10^2
L_y relative to ^{83m}Kr (32.1 keV)

arge Yield

ht Yield

MP signal efficiency



gorithm:S1 is 'photons detected' instead of total S1
t lowest energies, simply an integer count of PMT

Energy Calibration: detector-specific gain factors g1 =
: 0.003 phd/photon and g2 = 12.1 ± 0.8 phd/electron
asured in situ

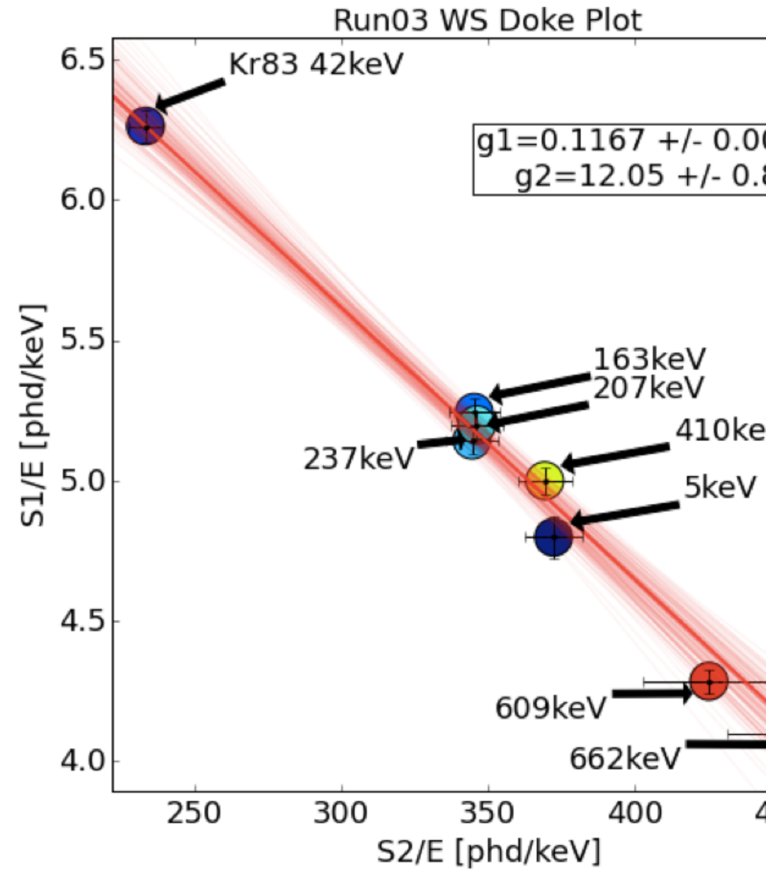
MT arrays used to estimate S2 size (compare to
n-only for 2013 analysis).

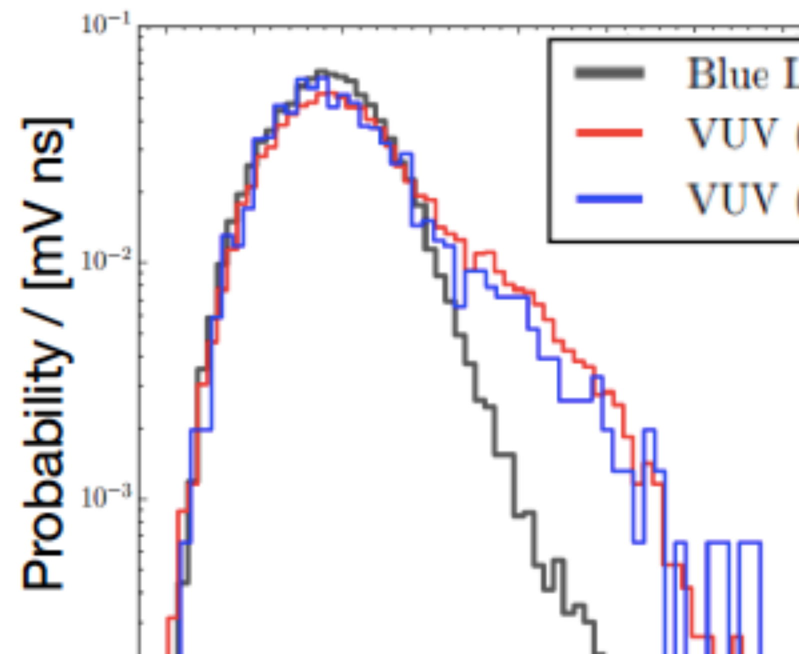
vements to the gamma-ray background model to
reproduce ER spatial distribution.

R Calibration, with a new lower energy threshold of
$/_{nr}$

ted likelihood of 2 phe from 1 VUV photon, in situ

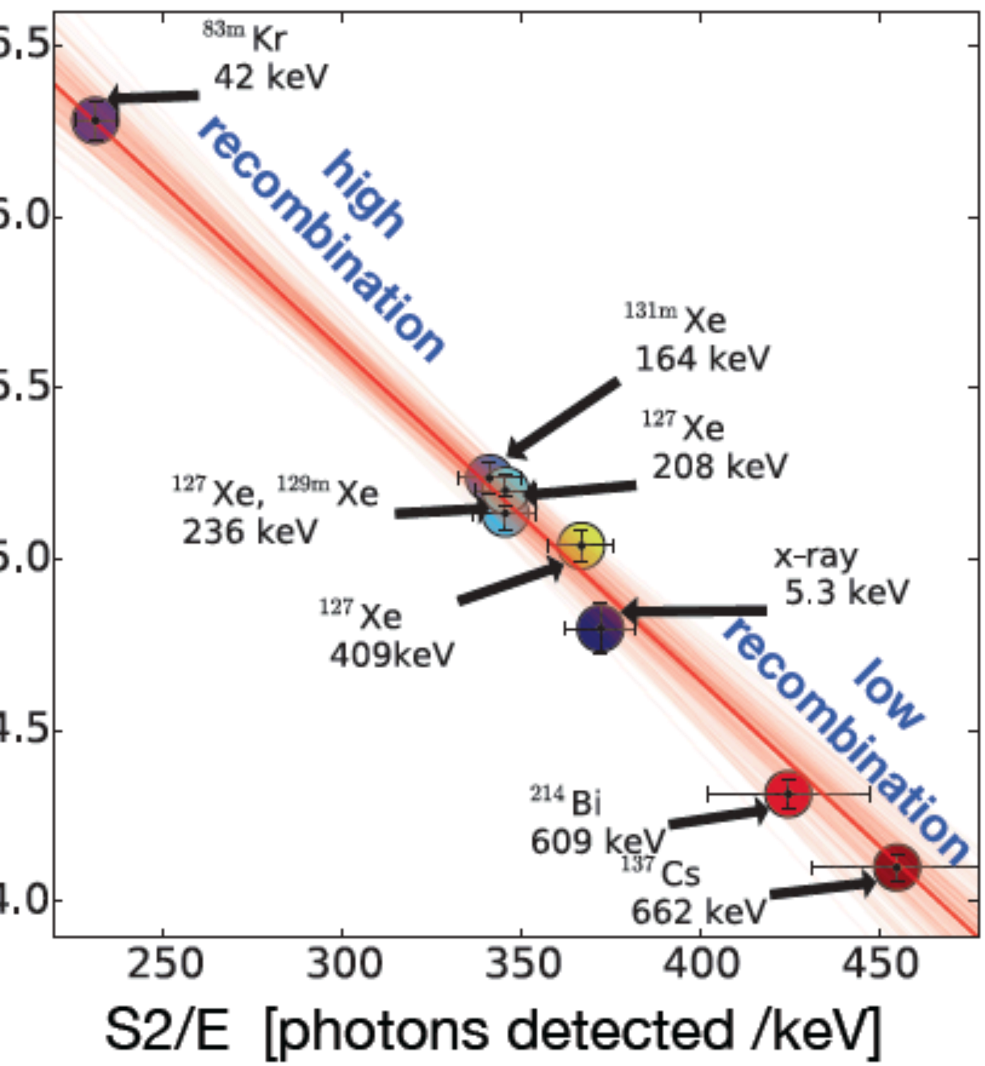
of electric field non-uniformity near detector edges
ted using ^{83m}Kr data





Precise Detector Efficiencies and Gains

e plot' analysis:
ron recoils all start with the same [excitation:ionization] ratio.
gy-dependent recombination **then moves quanta from one category to the other**
everage this 1-to-1 correspondence of quanta**, and fit for signal-per-quanta**.



$$S1/E = \frac{n_\gamma}{(n_\gamma + n_e)} \times \frac{g_1}{W}$$

$$S2/E = \frac{n_e}{(n_\gamma + n_e)} \times \frac{g_2}{W}$$

W = 13.7

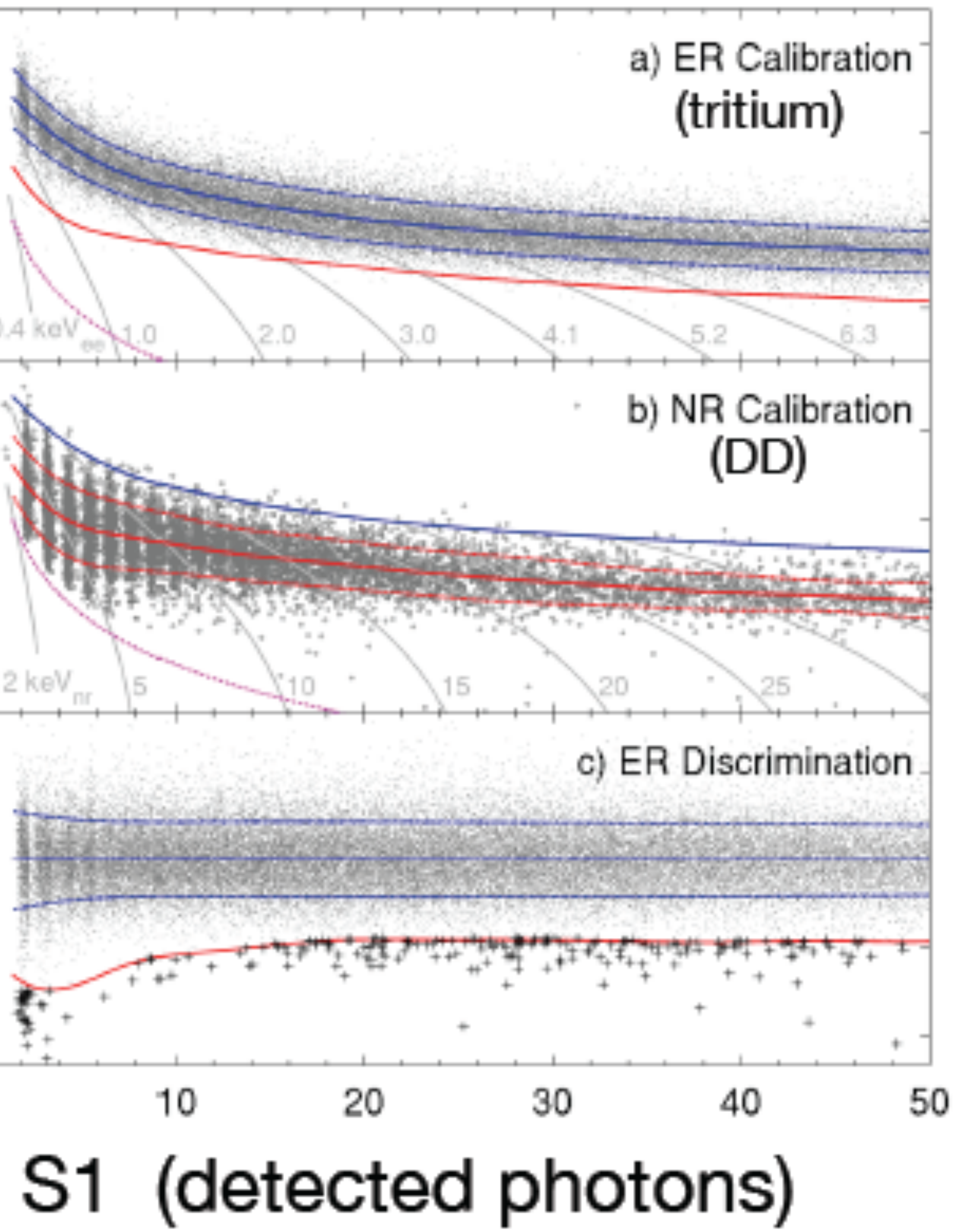
$$\left(\frac{S1}{E}\right) = \left(\frac{g_1}{W}\right) - \left(\frac{S2}{E}\right)\left(\frac{g_1}{g_2}\right)$$

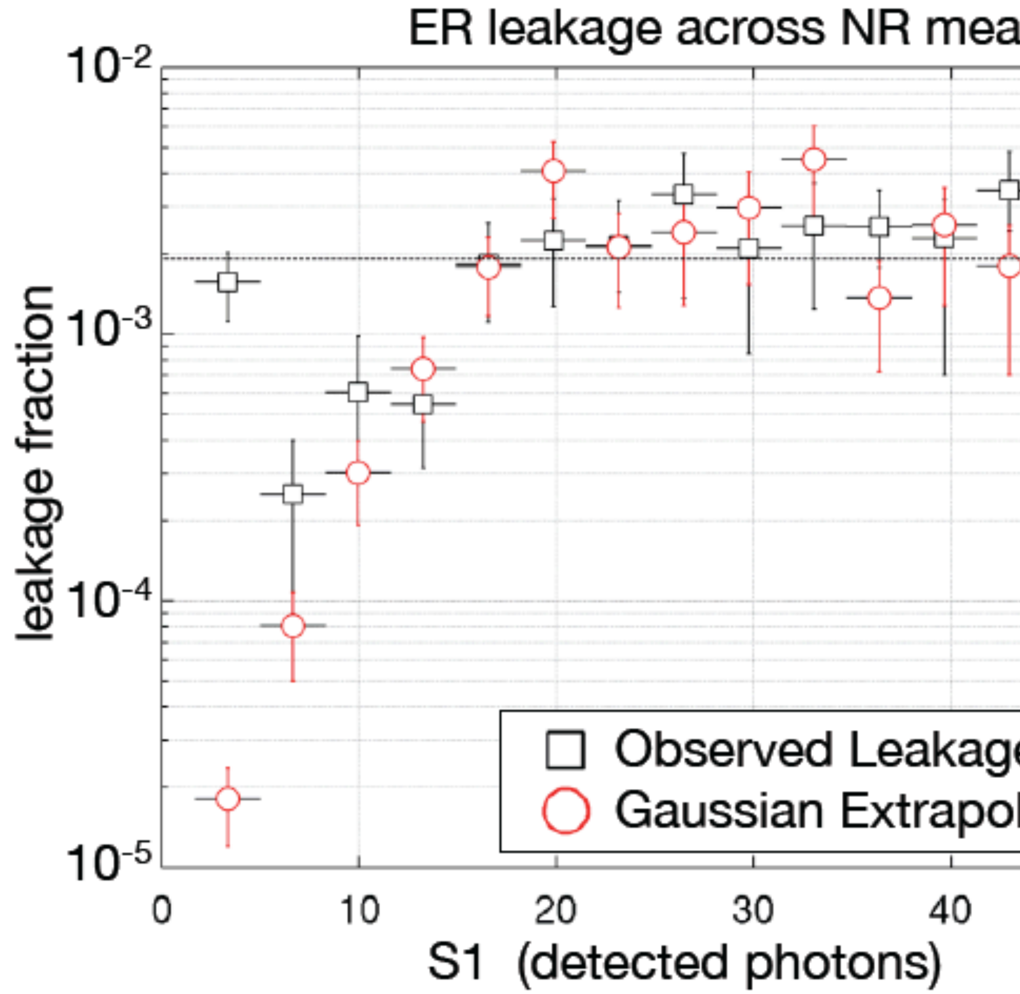
result:

$$\langle S1 \rangle\,[\mathrm{phd}] = [0.1167 \pm 0.003]\, n_\gamma$$

$$\langle S2 \rangle\,[\mathrm{phd}] = [12.05 \pm 0.83]\, n_e$$

Electron Recoil / Nuclear Recoil Discrimination





Increased Fiducial Size and Detector Exposure

nal 10 live-days of data incorporated into analysis

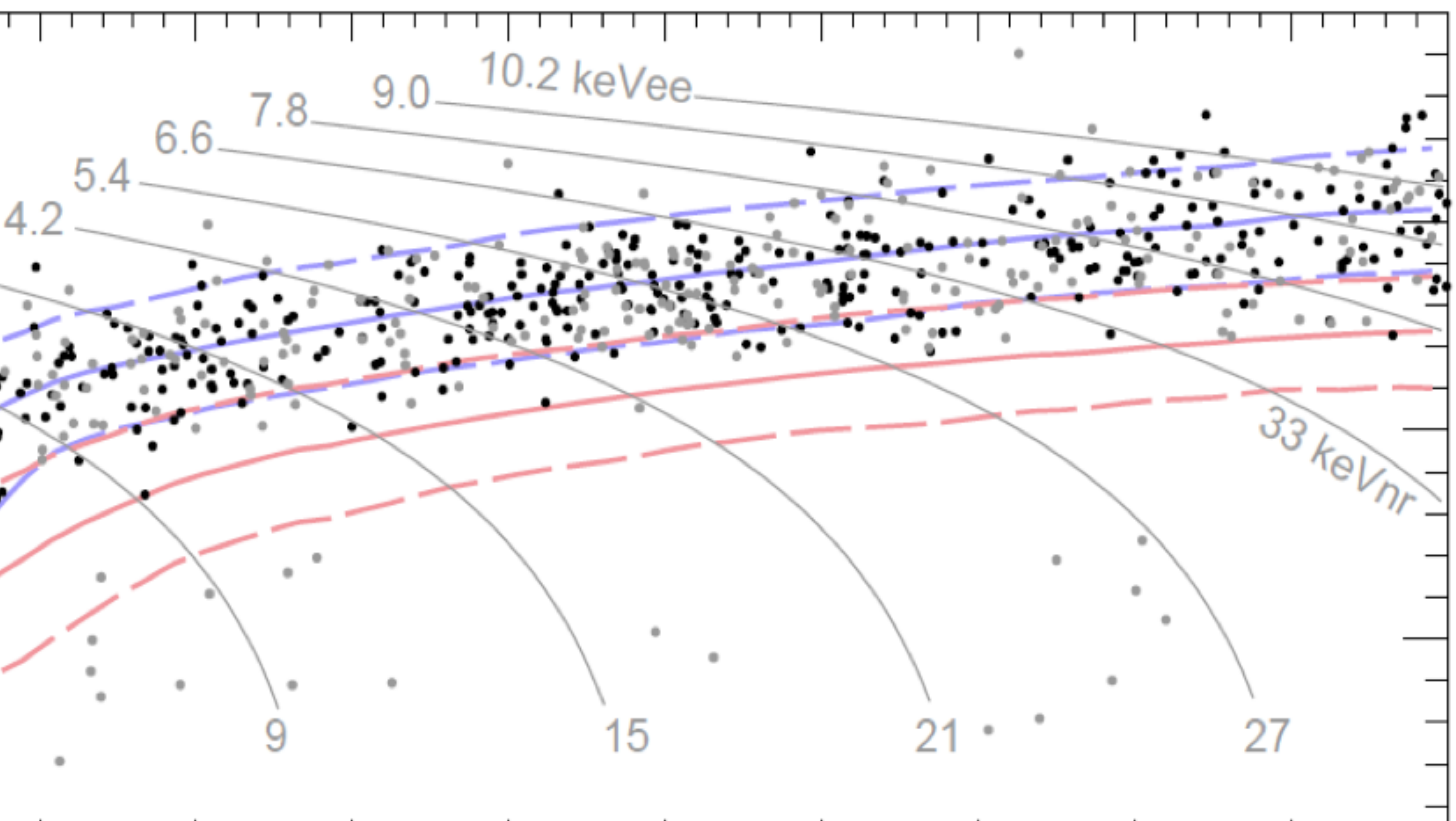
ed fiducial volume enabled by modeling of background wall events

3: radius = 18 cm, fiducial mass = 118 kg

5: radius = 20 cm, fiducial mass = 145 kg

Overall 40% increase in detector exposure

d range of S1 and S2 sizes: 1 phd < S1 < 50 phd, S2 > 150 phd



591 events observe

589 events predicte

background model

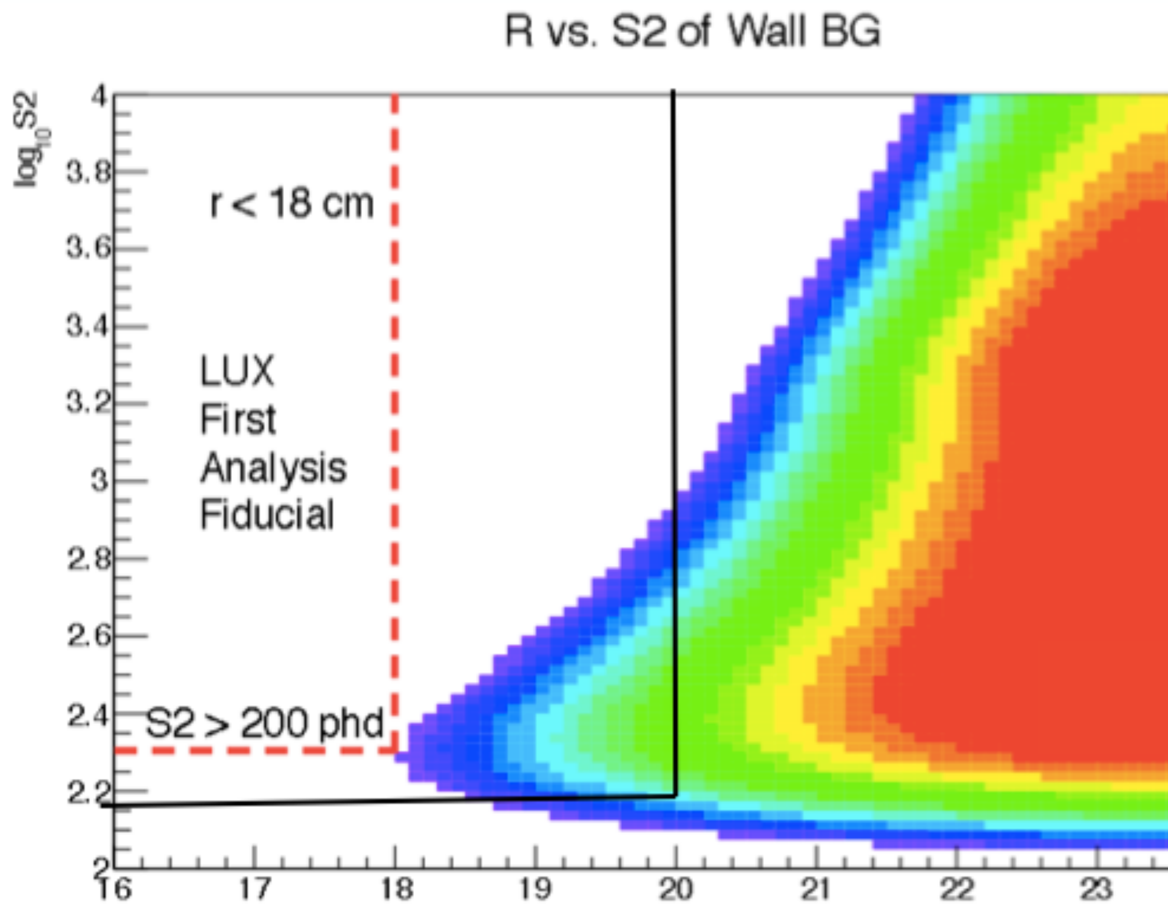
nprovements to Background Mode

inant background: low-energy ER
etector components + contaminants
n-daughters) in the Xe

in improvements:

e detailed modeling of detector
struction components

l events (e.g. ^{222}Rn - ^{206}Pb absorbed
PTFE) empirically modeled



minant backgrounds, not included in the model:

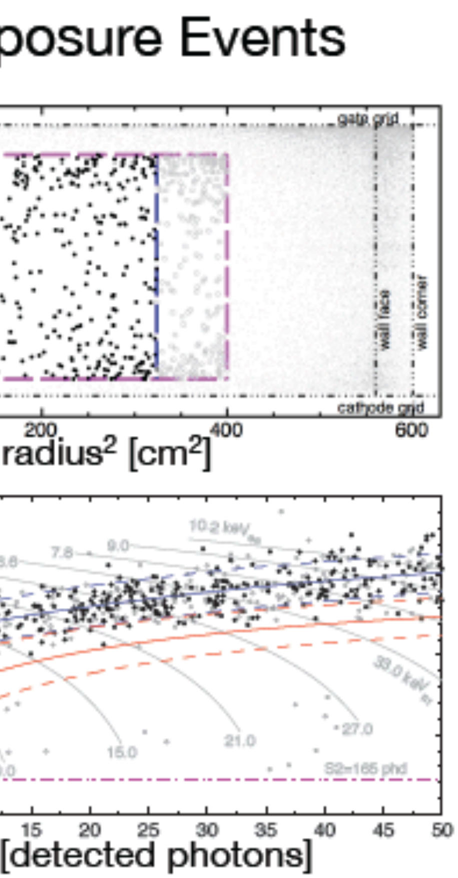
ected neutron background using revised cuts: 0.08 ± 0.01 NR events

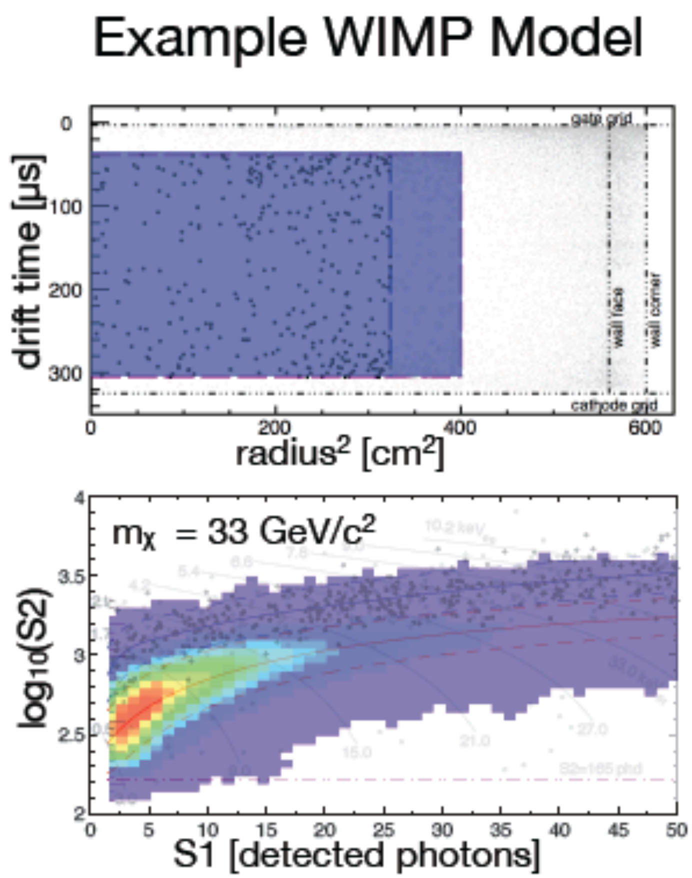
S2 coincidence: 1.1 total events

olar neutrino scattering: 0.10 total events

Profile Likelihood Ratio in [r, z, S1, logS2]

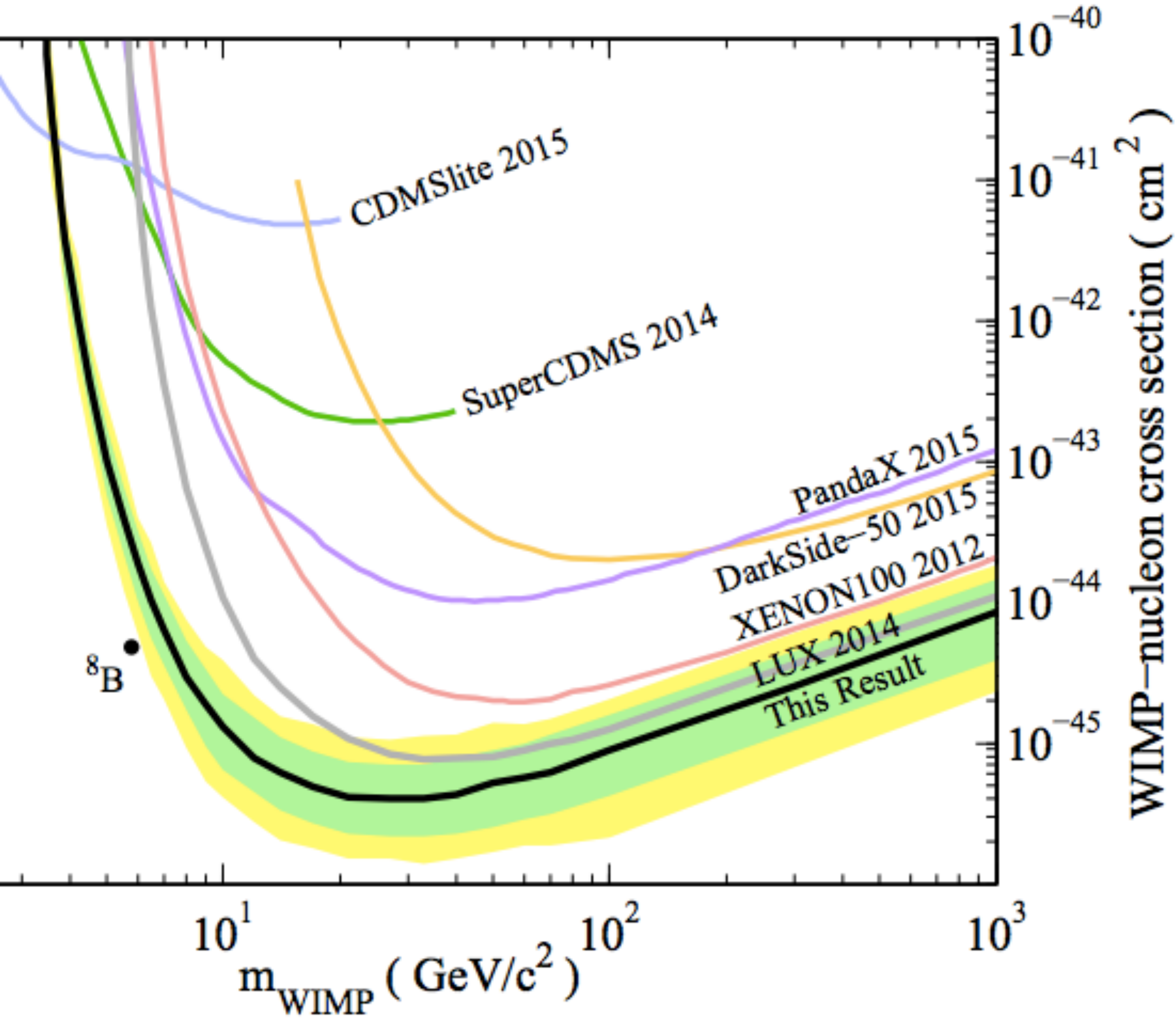
Both ER and NR response is precisely calibrated, so PLR model uncertainties are s
Dominant detector response uncertainties included,
but have minimal effect on limits (<20% at all masses)





	Parameter	Constrai
	Lindhard k	$0.174 \pm 0.$
	S2 gain ratio: $g_{2,\mathrm{DD}}/g_{2,\mathrm{WS}}$	$0.94 \pm 0.$
background rates	Low-z-origin γ counts: $\mu_{\gamma,\mathrm{bottom}}$	172 ± 7
	Other γ counts: $\mu_{\gamma,\mathrm{rest}}$	247 ± 1
	β counts: μ_β	55 ± 2
	^{127}Xe counts: $\mu_{\mathrm{Xe\text{-}127}}$	91 ± 2
	^{37}Ar counts: $\mu_{\mathrm{Ar\text{-}37}}$	-
	Wall counts: μ_{wall}	24 ± 7

LUX 2015 WIMP-Nucleon Interaction Limit



- Improved sensitivity
  mass WIMPs over LU
  result
  - Minimum kinemat
    accessible mass 3.
    (compare to 5.2 G
- 23% improvement in
  high-mass WIMPs

New minimum spin-independent cross section limit:
6×10^{-46} cm^2 (0.6 zb) for 33-GeV WIMPs

LUX-ZEPLIN

LZ = LUX + ZEPLIN

2 institutions currently
bout 200 people

or Underground Physics (Korea)
bra (Portugal)

Russia)
gh University (UK)
ty of Liverpool (UK)
College London (UK)
ty College London (UK)
ty of Oxford (UK)

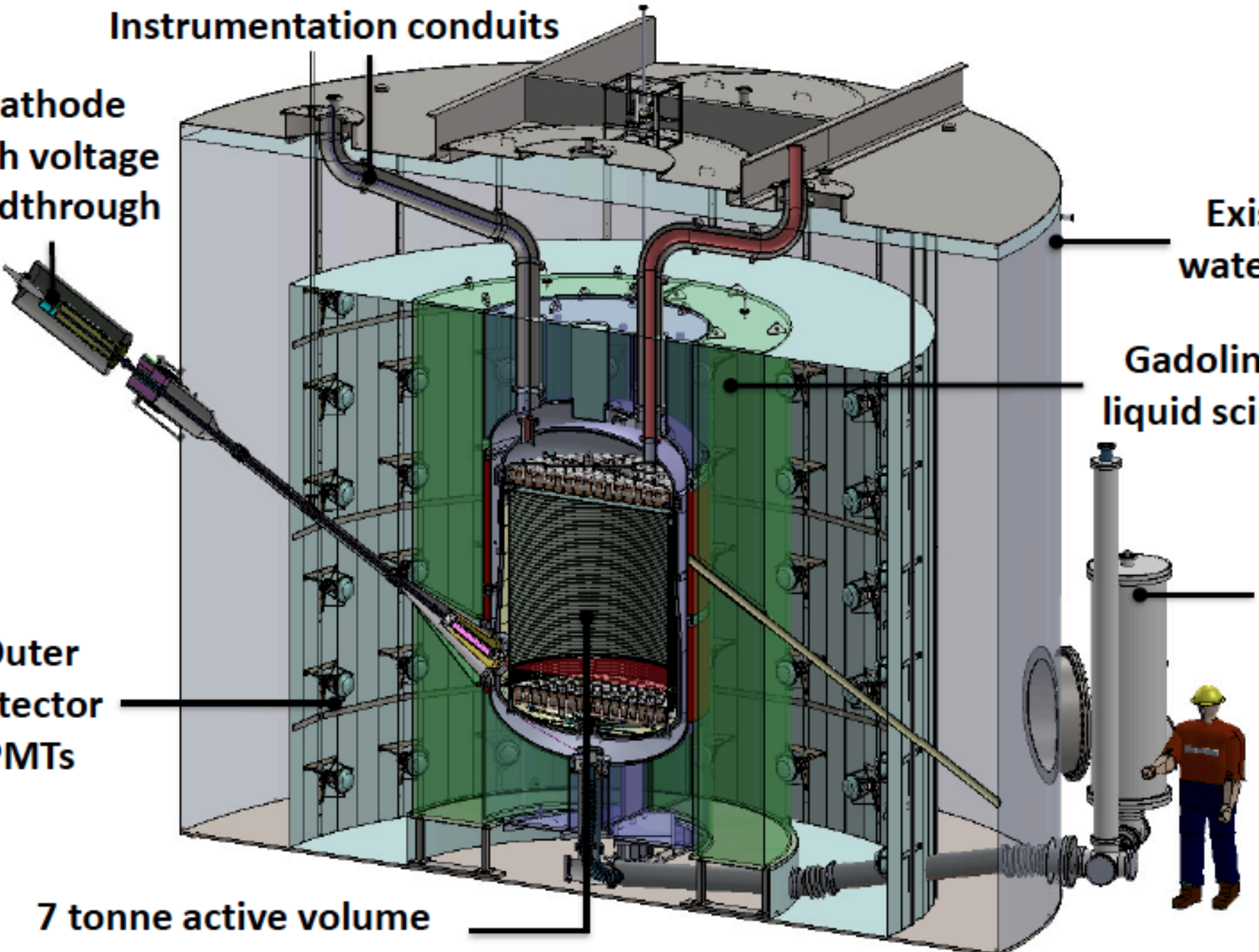
University of Alabama
University at Albany SUNY
Berkeley Lab (LBNL)
University of California, Berkeley
Brookhaven National Laboratory
Brown University
University of California, Davis
Fermi National Accelerator Laboratory
Kavli Institute for Particle Astrophysics & Cosmo
Lawrence Livermore National Laboratory
University of Maryland
University of Michigan
Northwestern University
University of Rochester
University of California, Santa Barbara
University of South Dakota
South Dakota School of Mines & Technology
South Dakota Science and Technology Authority
SLAC National Accelerator Laboratory
Texas A&M
Washington University

Scale Up ≈ 50 in Fiducial Mass

LZ

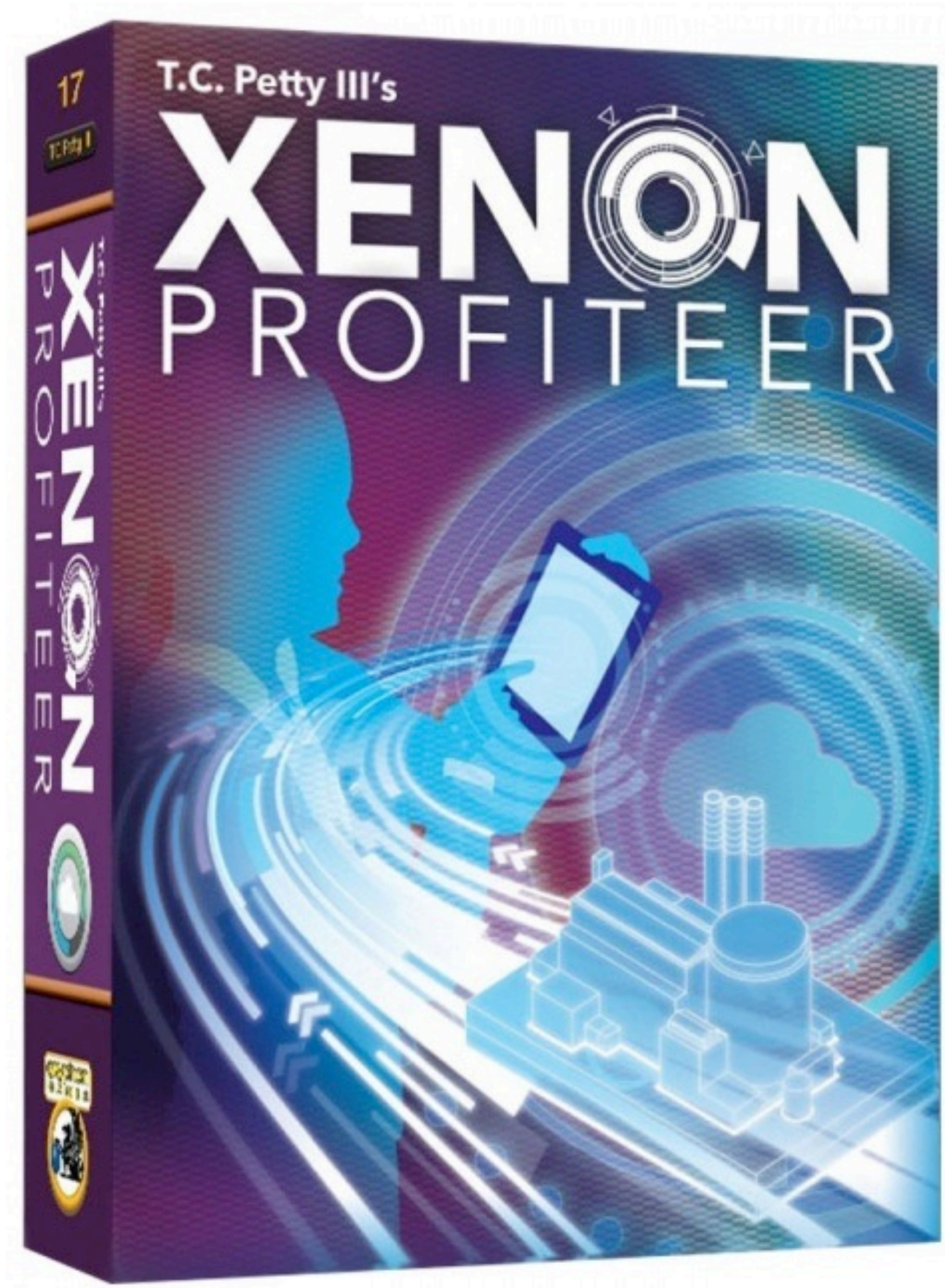
s – 10 T
ive Mass – 7 T
ucial Mass – 5.6 T

LZ Detector Overview



n Xenon Profiteer, you use your entrepreneurial spirit and an
ir Separation facility to isolate valuable Xenon and make a profit.

ofiteer is a highly thematic,
struction, euro game for 2-4
urs in which each player takes
eir own Air Separation Facility
Xenon from their Systems to
crative contracts. You will also
xpand your facility by building
pipelines, and acquiring new
nd connecting them to your
sole."



Gryphon and Eagle Games

Key Design Points

active tonnes of LXe can yield 2 x 10^{-48} cm^2 sensitivity in about
ree years of running

6 tonne fiducial volume, 1000 days

equires all detector systems working together

Xe detector with good light collection, reasonable background rejectio
(ER discrimination) and good signal detection efficiency

Sophisticated veto system: skin (outside active Xe region) + scintillator
water allows maximum fiducial volume to be obtained, maximizes use
Xe and substantially increases reliability of background measurements

Control backgrounds, both internal (within the Xe) and external from
detector components/environment

Design Status Summary

onceptual, and in some cases more advanced esign, completed for all aspects of detector

onceptual Design Report can be viewed on arXiv

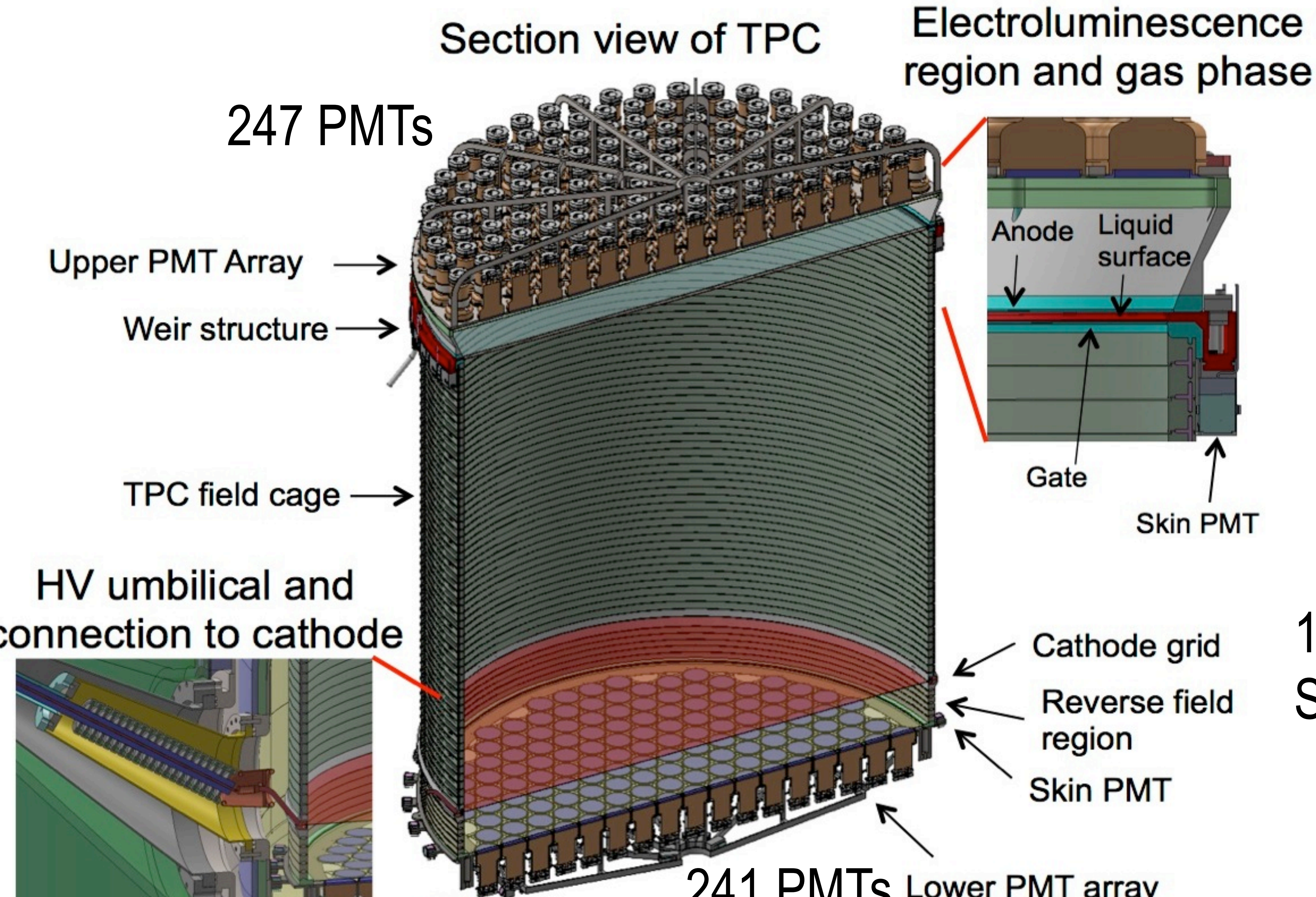
cquisition of Xenon started

rocurement of PMTs and cryostat started

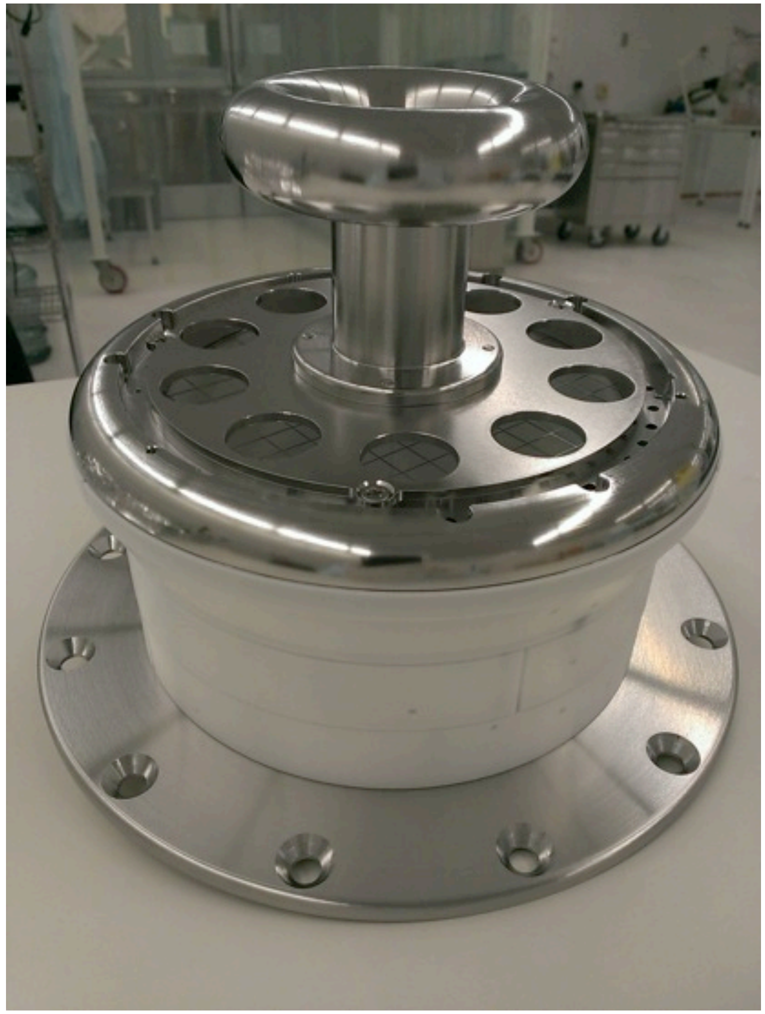
ollaboration – wide prototype program underway uide and validate design

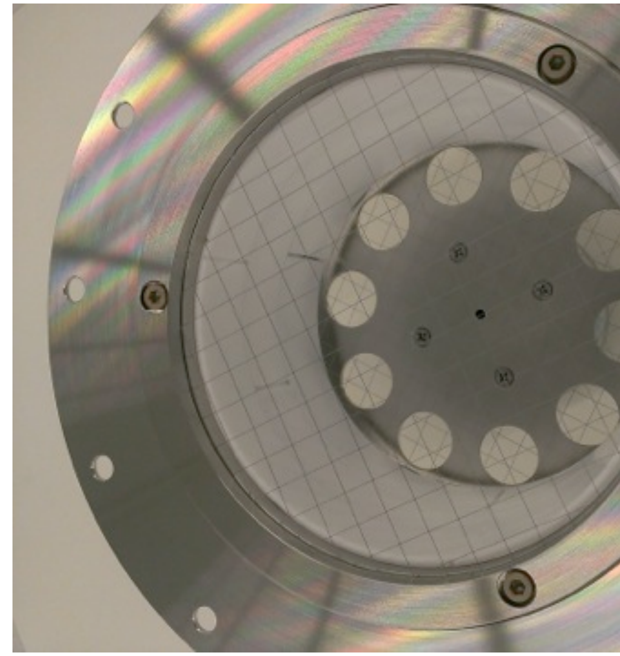
ackgrounds modeling and validation well underw

Xe TPC Detector



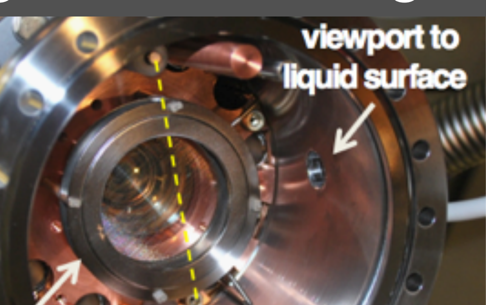
High Voltage Studies





Prototype of highes
region tested in LA

grid tests ongoing



- LZ cathode nominal operating goal: 100 kV (~ 700 V/cm)
- Feedthrough prototype tested to 200 kV
- Prototype TPC for 100 kg LXe system being tested at SLAC
- HV prototyping expanding at Berkeley

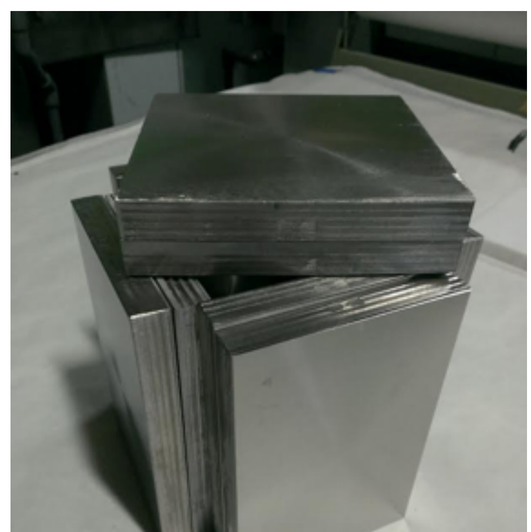
Extensive Calibration

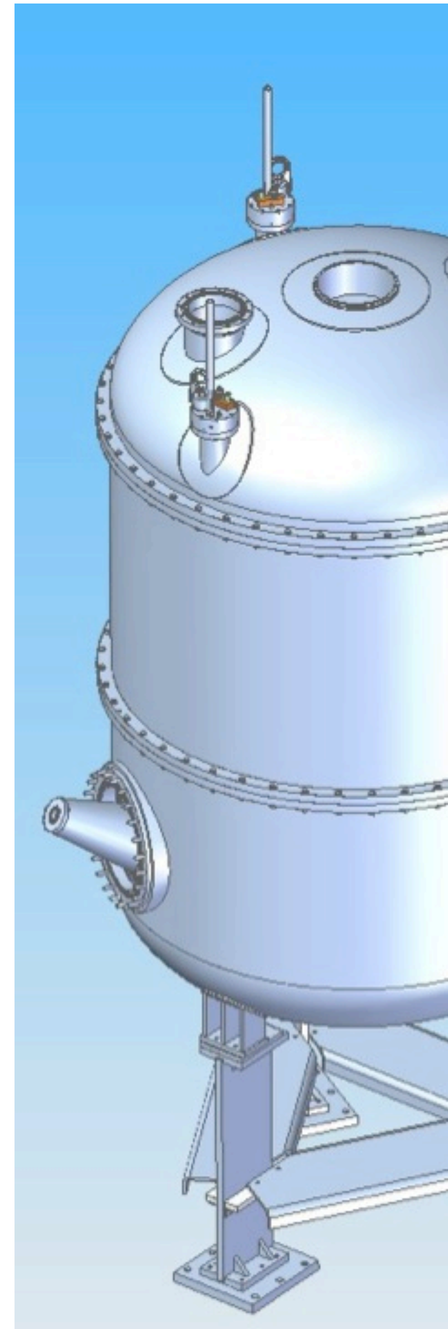
UX has led the way to detailed calibrations. LZ will build on this
d do more.

e in LUX and will be done in LZ	Not done in LUX, but will do in LZ
(routine, roughly weekly)	Activated Xe (^{129m}Xe and ^{131m}Xe)
ted methane (every few months)	^{220}Rn
nal radioisotope neutron sources	AmLi
nal radioisotope gamma sources	YBe
eutron generator(upgraded early year to shorten pulse)	

Cryostat Vessels

- responsibility
- v background Ti chosen as cryostat material
- on Ti slab for all vessels (and other parts)
  eived and assayed
- ntributes < 0.05 NR+ER counts in fiducial
  ume in 1,000 days after cuts



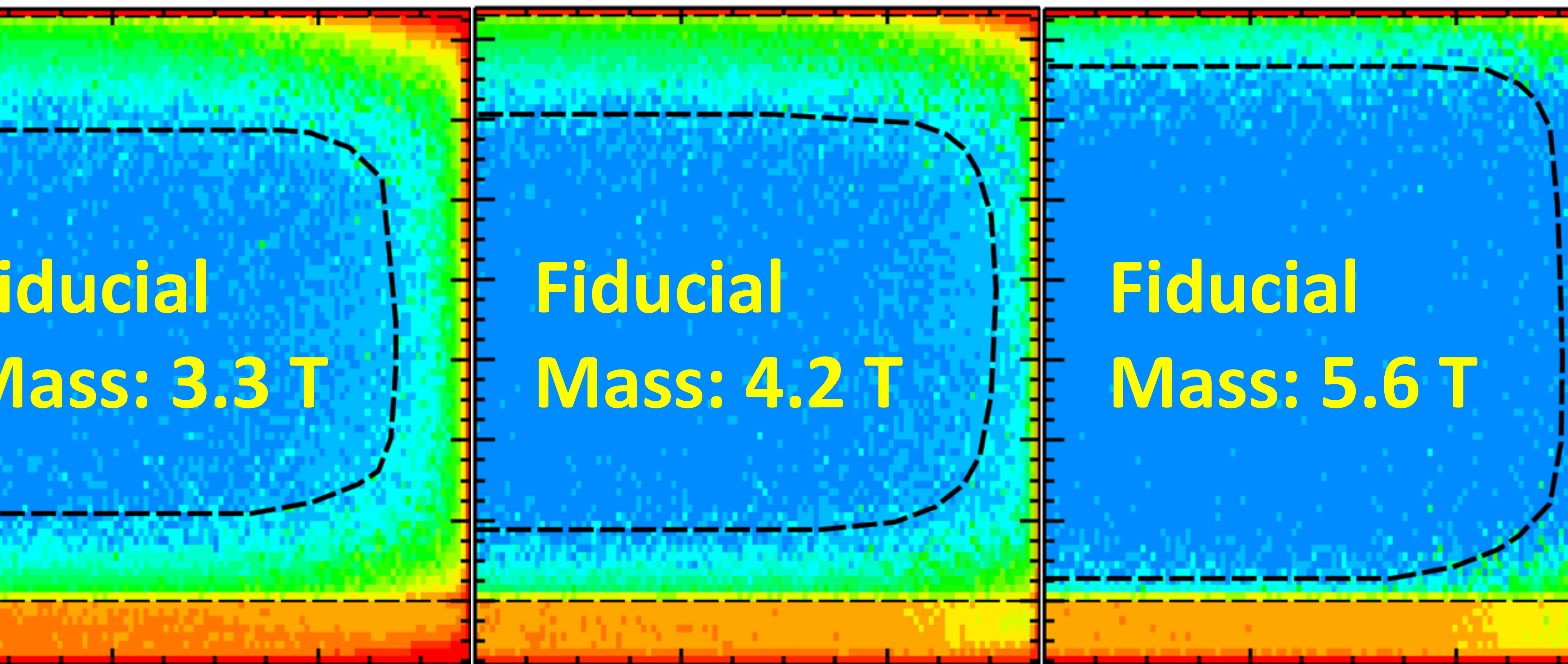


How to maximize the WIMP target ma

vo-component outer detector:
- 0.75 m thick Gd-loaded scintillator
- instrumented Xenon “skin”
- tag neutrons and gammas

in-situ **monitoring of residual backgrounds!!!**

Xe-TPC Only **Xe-TPC + “skin”** **TPC + skin + Gd-sci**

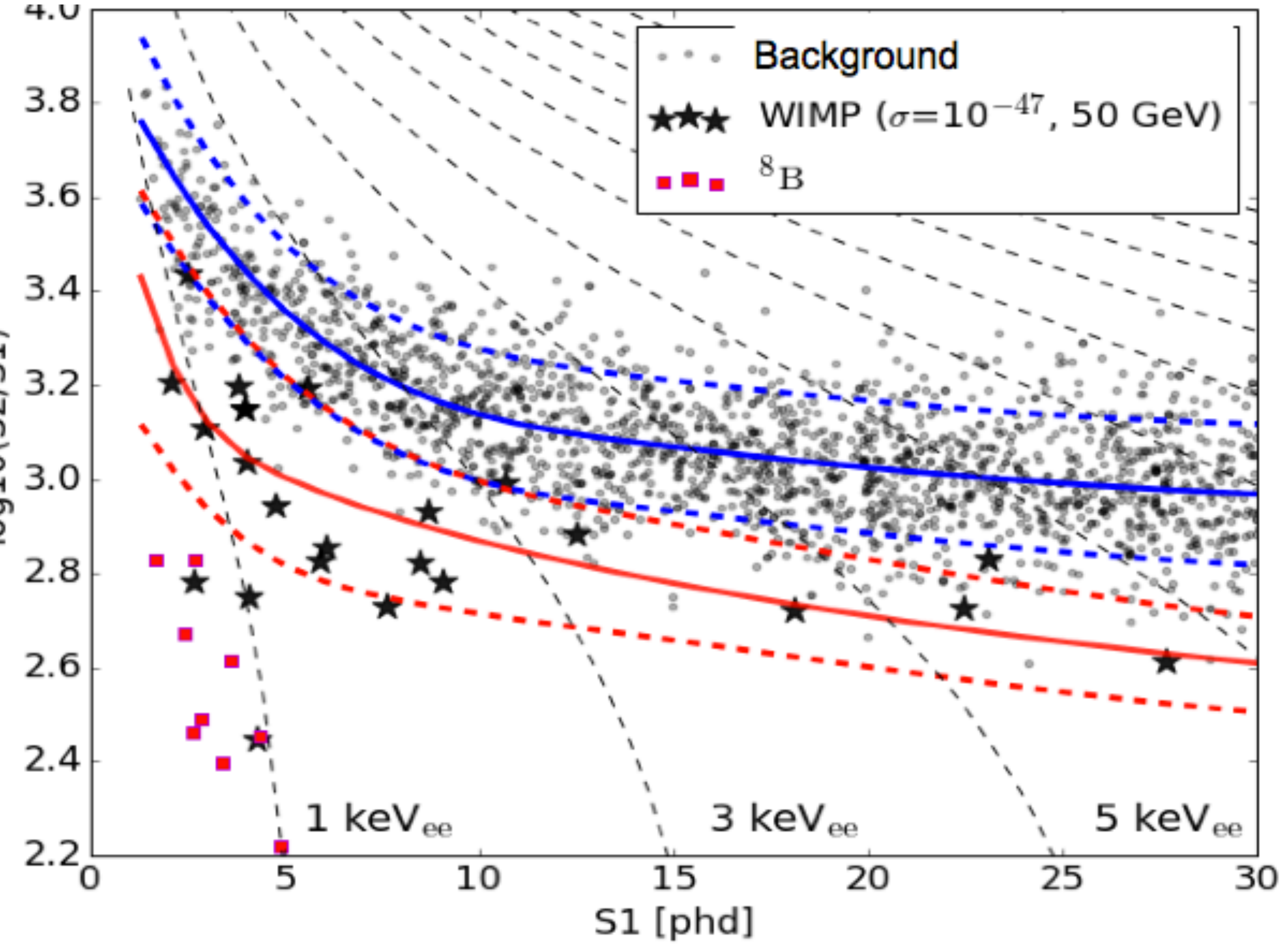


LZ Projected Backgrounds

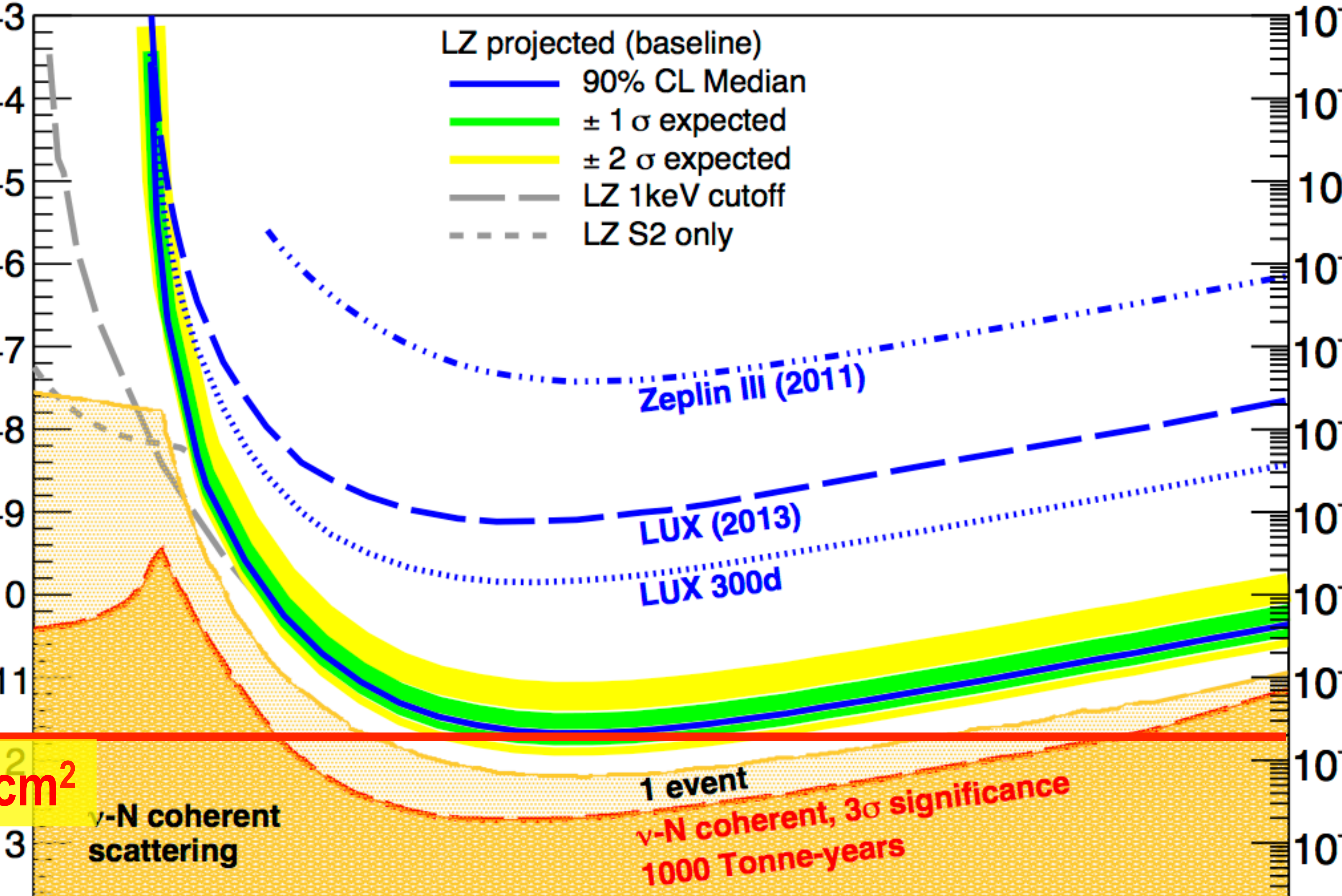
pected backgrounds for 5.6 T fiducial - 1,000 days

Item	Mass kg	U mBq/kg	Th mBq/kg	^{60}Co mBq/kg	^{40}K mBq/kg	n/yr	
ITs	93.7	2.7	2.0	3.9	62.1	373	1
ses	2.7	74.6	29.1	3.6	109.2	77	0
ssels	2,140	0.09	0.23	≈0	0.54	213	0
	122	1,507	1,065	≈0	3,900	20,850	0
ponents	-	-	-	-	-	602	9
ponents							1
radionuclides (Rn, Kr, Ar)							5
							5
(ν-e, ν-A)							2
ts							3
kground events discrimination, 50% NR acceptance)							1

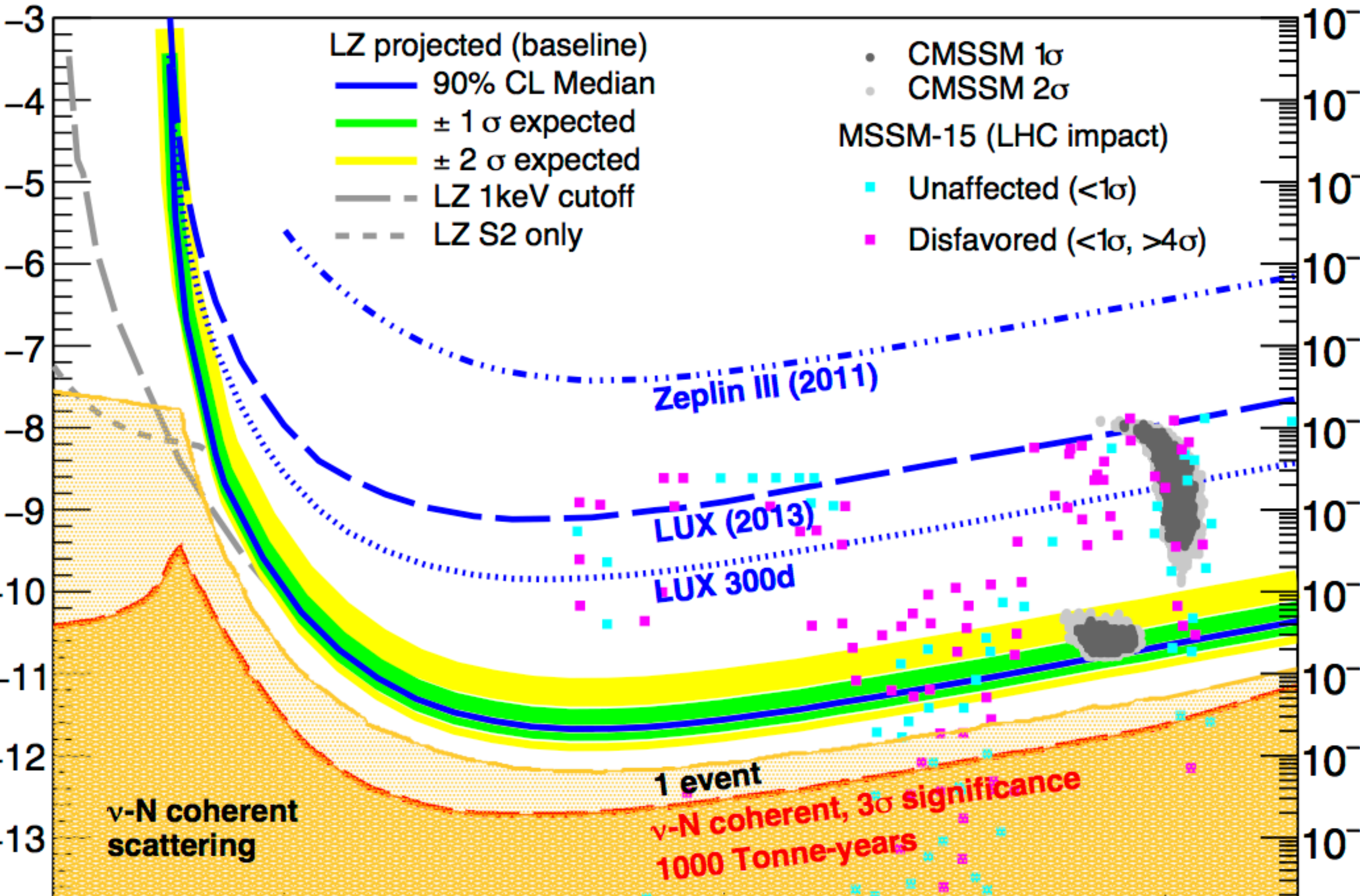
Example LZ Exposure



(LZ 5.6 Tonnes, 1000 live days, 6 keV_{nr} analysis threshold)



Sensitivity with SUSY Theories



Neutrino Physics with LZ

trinoless Double Beta Decay of ^{136}Xe

se self-shielding to reduce gamma-ray backgrounds in a 1-2 tonne fiducial m

ojected sensitivity: 90% confidence level $T^{0\nu}_{1/2}$ of 2×10^{26} years

nriching the Xe target could increase this to ~ 2×10^{27} years

urrent limit is 2.6×10^{25} years (preliminary) from KamLAND-Zen

rnal Neutrino Physics

olar neutrinos

- Expect about 850 pp neutrino events between 1.5 and 20 keV_{ee}

upernova neutrinos

- Via flavor-blind coherent neutrino-nucleus scattering
- For a 10 kpc SN, LZ would see about 50 events with energy > 6 keV_{nr} and 100 events > 3

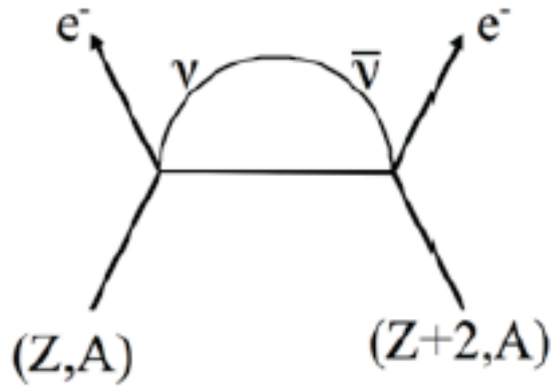
erile neutrinos

- Could use a 5 MCi ^{51}Cr source near LZ
- Excellent position reconstruction for better source normalization, higher sterile neutrino masses.

eutrino magnetic moment

- Sensitivity near astrophysical limit of 2×10^{-12} Bohr magnetons.

What is $0\nu\beta\beta$?



$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e-$

$2\nu\beta\beta$

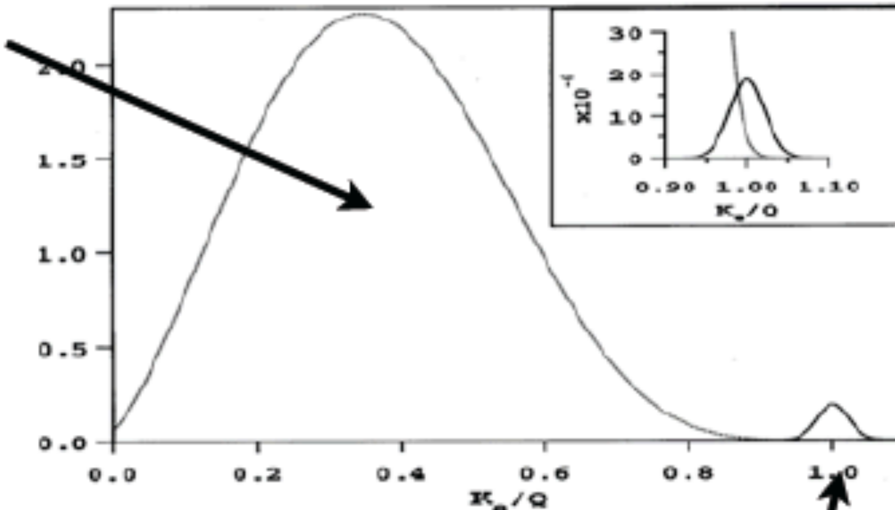


Figure from Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

$0\nu\beta$

- Happens only if the ν_e is its own anti-particle (Majorana particle)
- Discovery implies
  - existence of Majorana particles
  - lepton number violation
  - B-L violation

- **Signal: mono-energetic, single site peak at 2458 keV**

Keys to Sensitivity

- **Large mass of isotope**
  - To measure > 10^{25} year half-life, need > 10^{25} particles
- **Low-background at Q-value**
  - Signal is small compared to typical ambient radioactivity
- **Energy resolution at Q-value**
- **Multiple scatter rejection**
  - Main backgrounds are gamma which prefer to Compton scatter or pair-produce

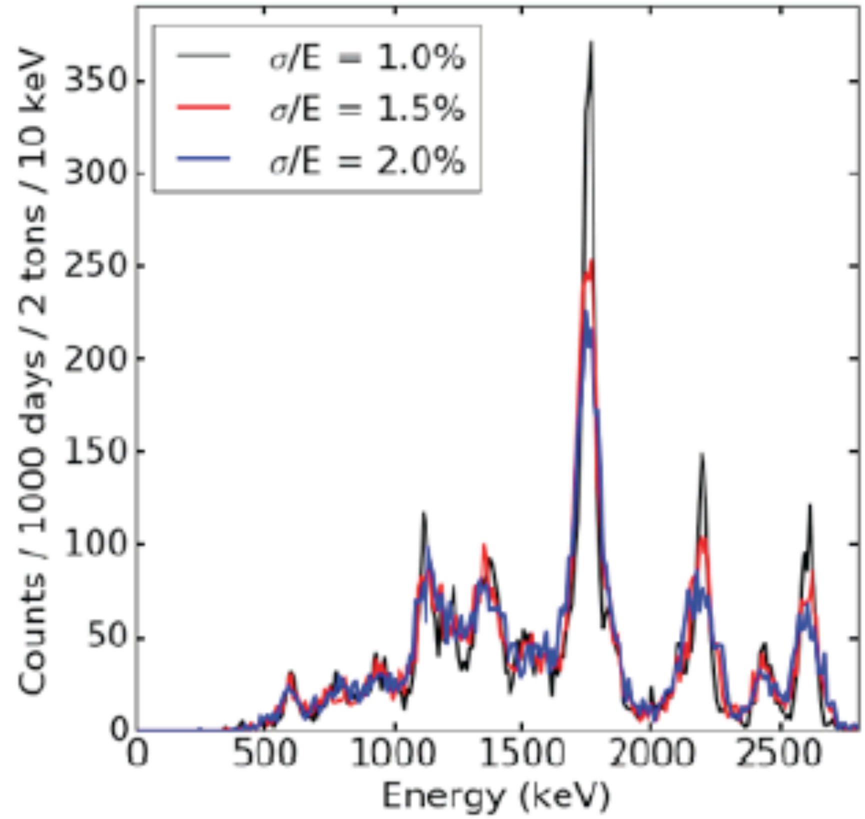
- 7 tons of active xenon => 620 kg ^{136}Xe (8.9% of natural Xe)
- Very low backgrounds
- Low-gain DAQ channel for dynamic range
- Use tight fiducial cut (≥ 2 tons) to reduce backgrounds
- Xe TPCs have strong multiple scatter rejection capabilities (Compton scatters and pair-production dominate for > 1 MeV gammas)
- Punchline: with **NO ADDITIONAL UPGRADES** LZ can be a competitive search for $0\nu\beta\beta$

Energy Resolution (σ/E)

- EXO-200 experiment: 1.5% (@ 2.458 MeV, noise dominated)
- PiXeY detector: 0.8% (@ 2.615 MeV)
- MiX detector: 1.0% (@ 1.33 MeV)
- LZ Requirement R-150004: 2.0% @ 2. MeV

Backgrounds

- Main background comes from Xe vessels and insulation
- Background from from vessel dominate
- Table is for 2-ton exposure, $\pm$ 2 σ window for 1000 days
  - **<u>NOT</u>** using optimized fiducial volume

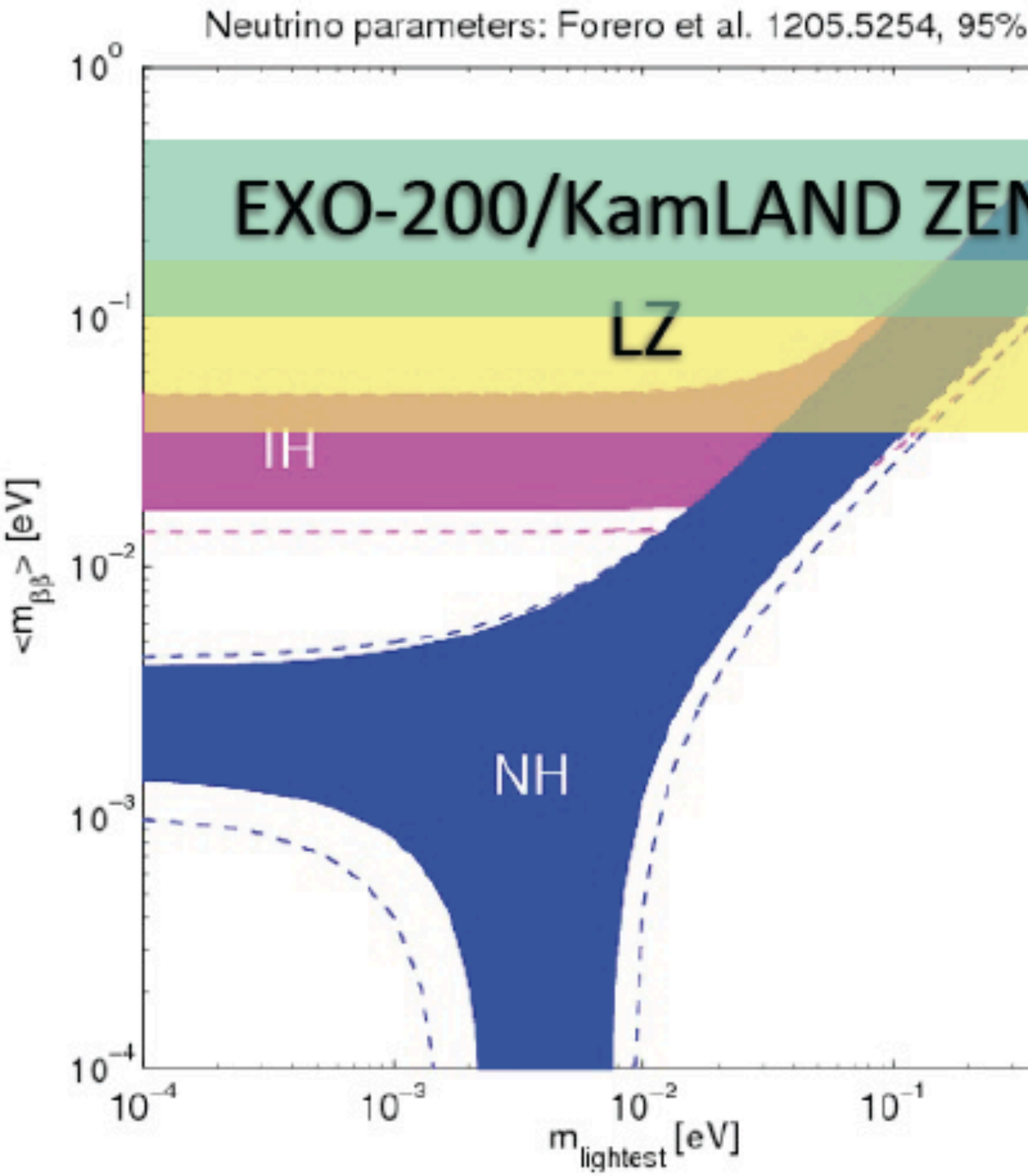


Item	1.0% σ/E	1.5% σ/E	2.0% σ/E
TPC PMTs	< .01	0.05	0.18
Skin PMTs	< .01	0.02	0.02
Xe Vessels	2.5	2.7	3.2
Vessel Seals	< .01	< .01	0.03

Sensitivity

	1.0%	1.5%	2.0%
-life	4.0 X 10^{26} years	2.5 X 10^{26} years	1.8 X 10^{26} years
trino s	35-110 meV	45-140 meV	60-160 meV

Limits based on Feldman-Cousins cut-and-count analysis on an optimized fiducial volume (for each scenario)



LZ Timeline (latest following budget reprofiling)

Month	Activity
March	LZ (LUX-ZEPLIN) collaboration formed
May	First Collaboration Meeting
September	DOE CD-0 for G2 dark matter experiments
November	LZ R&D report submitted
July	LZ Project selected in US and UK
April	DOE CD-1/3a approval, similar in UK Begin long-lead procurements(Xe, PMT, cry
April	DOE CD-2/3b approval, baseline, all fab star
June	Begin preparations for surface assembly @
July	Begin underground installation

Conclusions

- LXe is the pre-eminent target for WIMPs of mass > 4 GeV.
- New LUX analysis reaches a 90% exclusion limit of **6×10^{-46}**
- The LXe 2-phase approach benefits from continued improv in calibration techniques and understanding of background
- The LZ Project is well underway, with procurement of Xe, P and cryostat vessels started
- LZ commissioning to begin in 2019
- Extensive prototype program underway
- LZ sensitivity expected to reach **$1\text{-}2\times10^{-48}$ cm^2**

o has seen the WIMP?

ther I nor you.

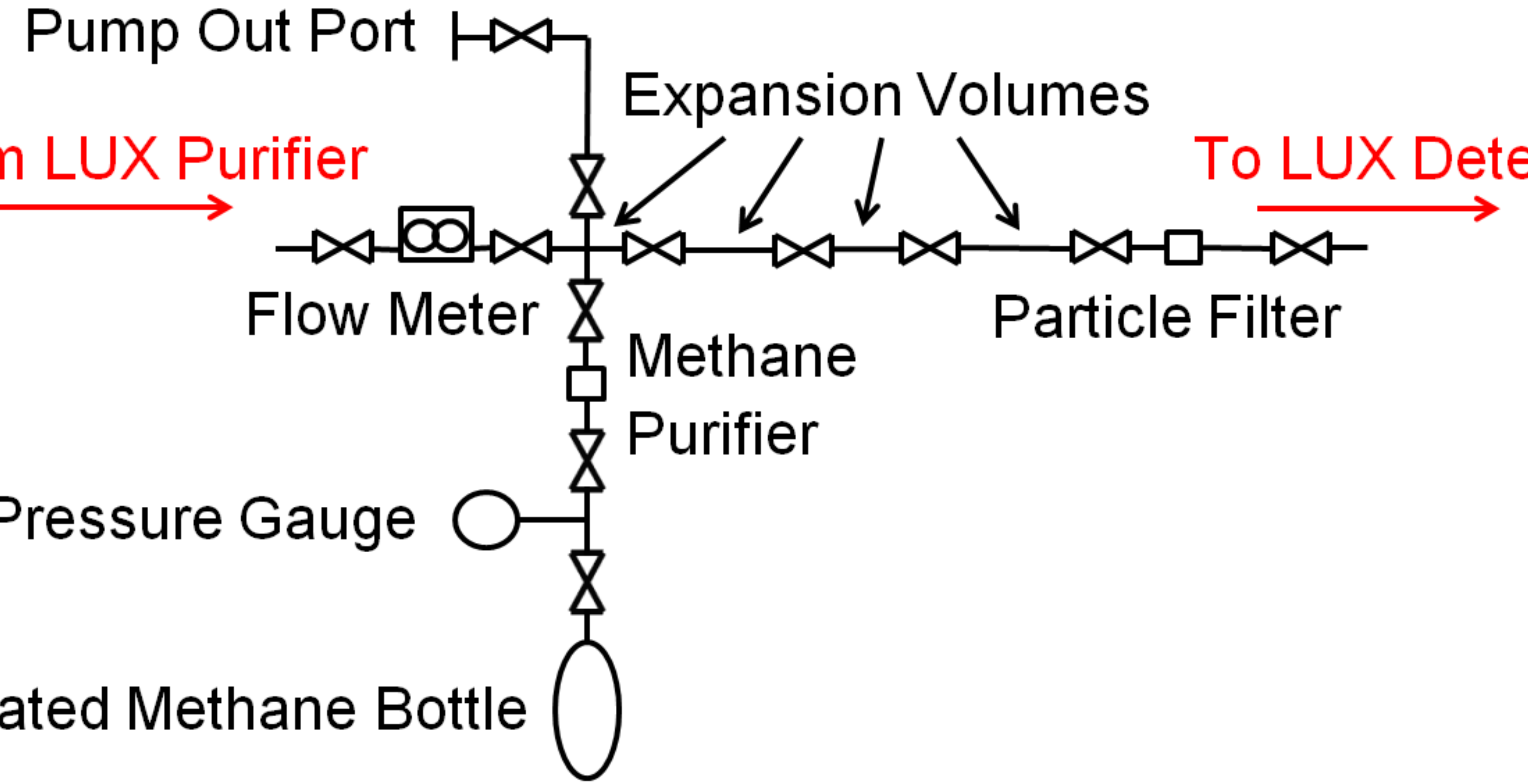
when the liquid xenon flashes in the time projection chambe

k Matter is passing through.

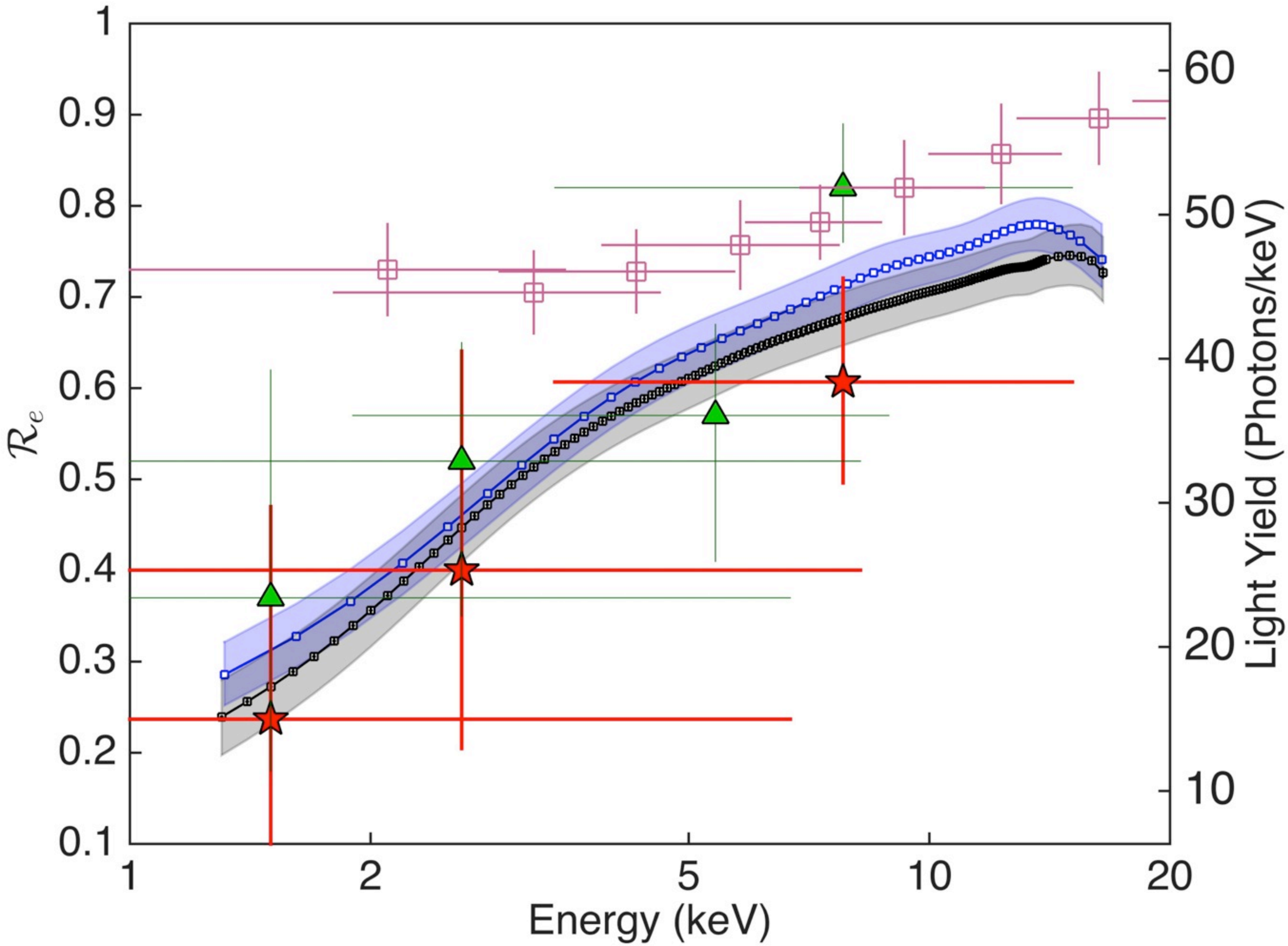
DM and Eva Allan

(with apologies to Christina Rossetti)

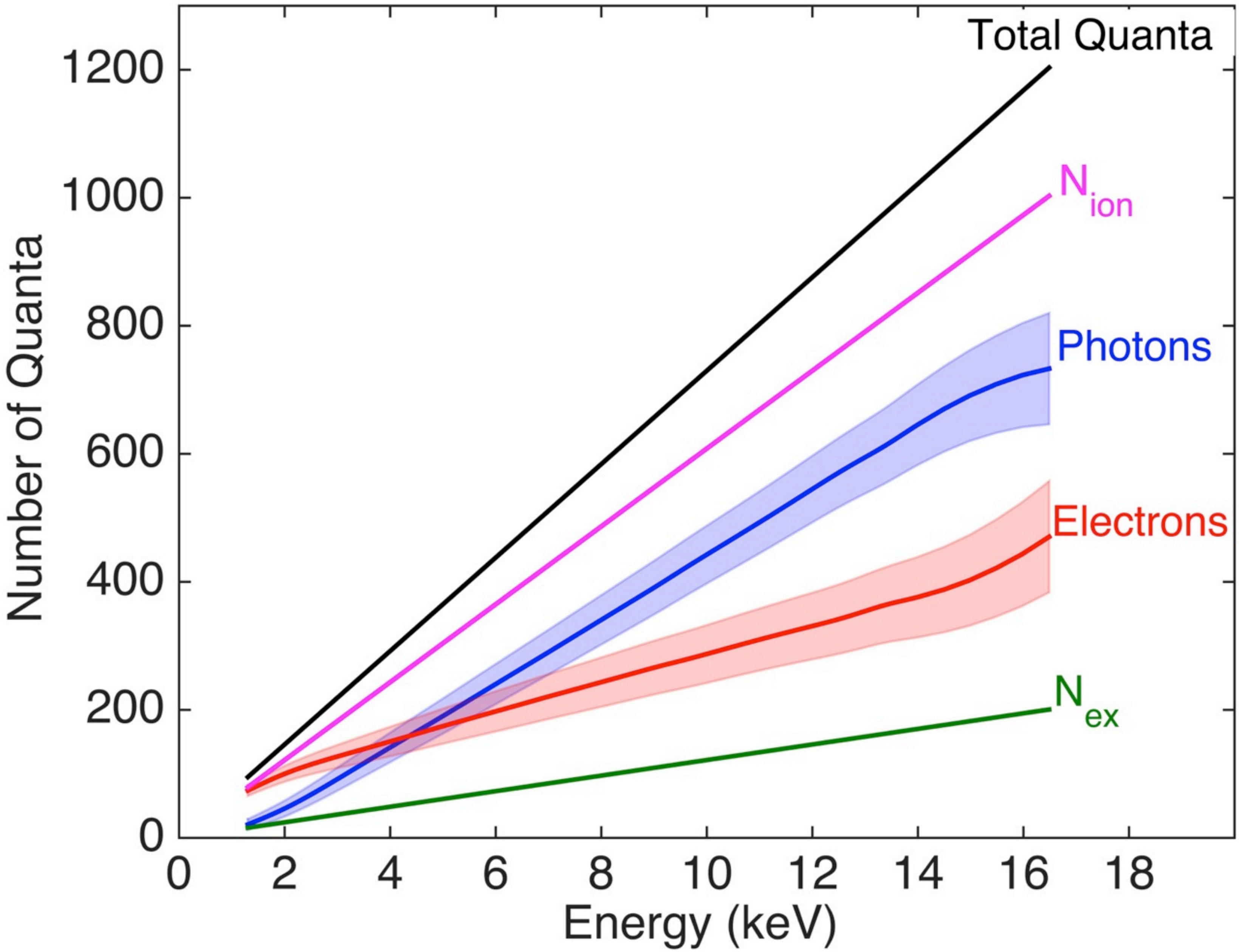
Tritiated Methane injection system



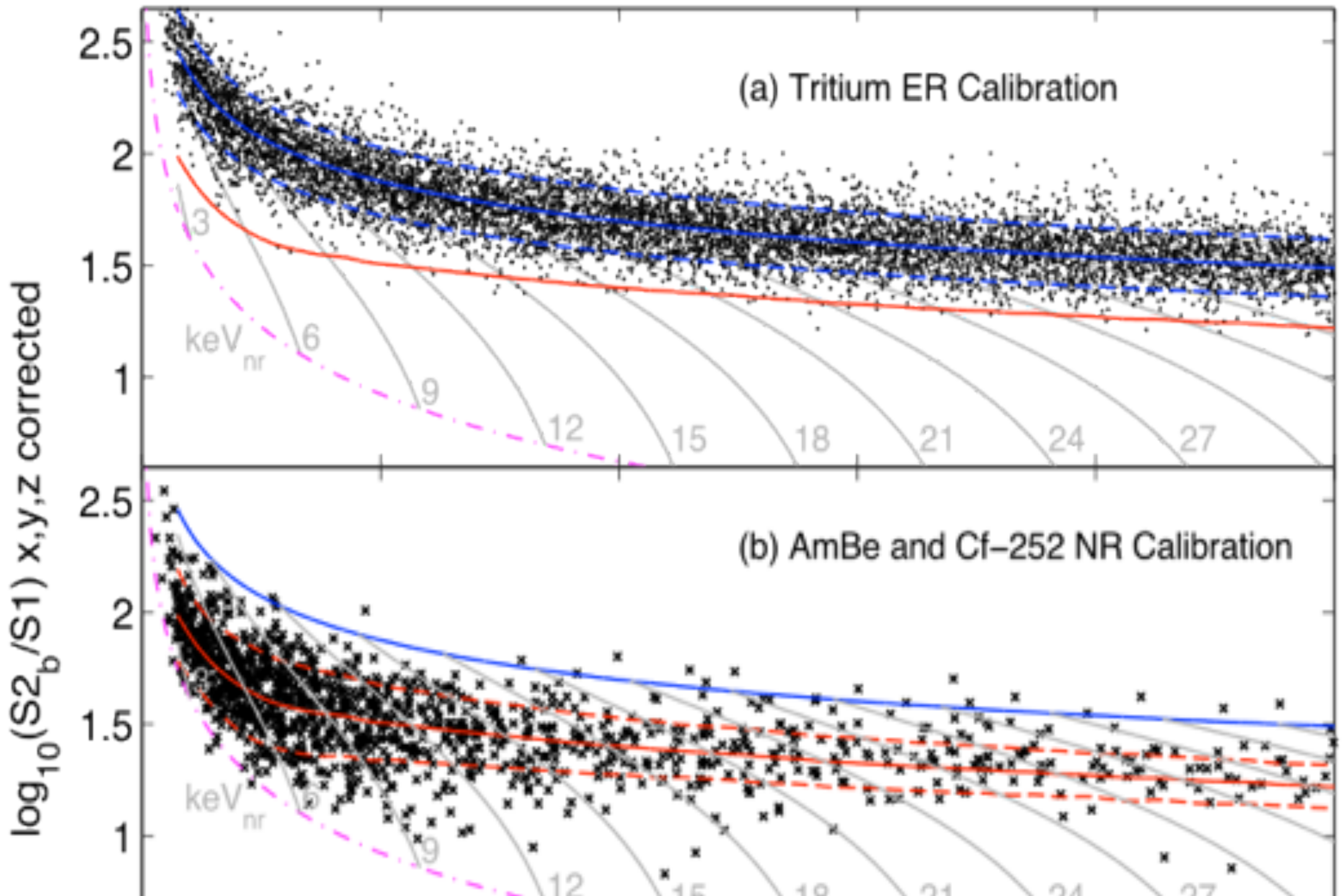
Recombination and Light Yield

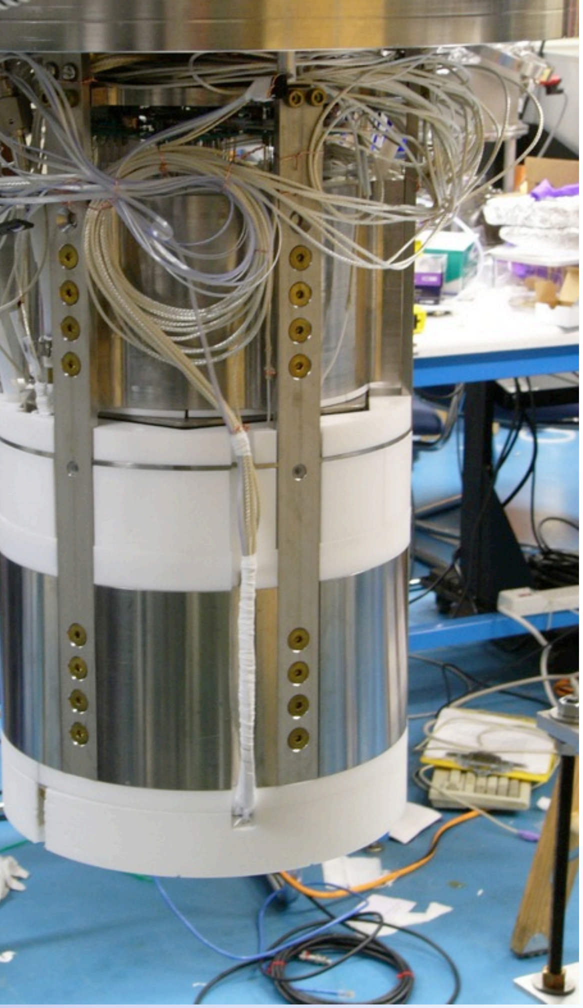


otal Quanta (electrons +photons) for electro recoils in LXe

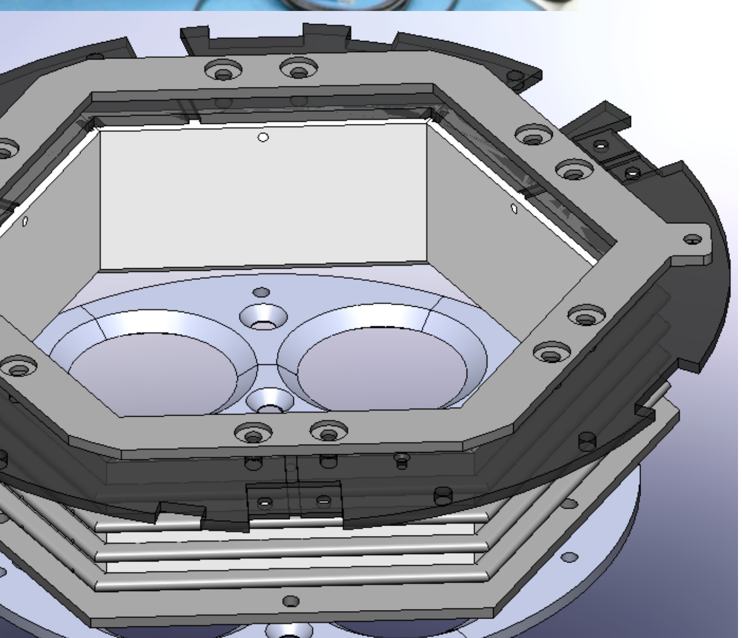


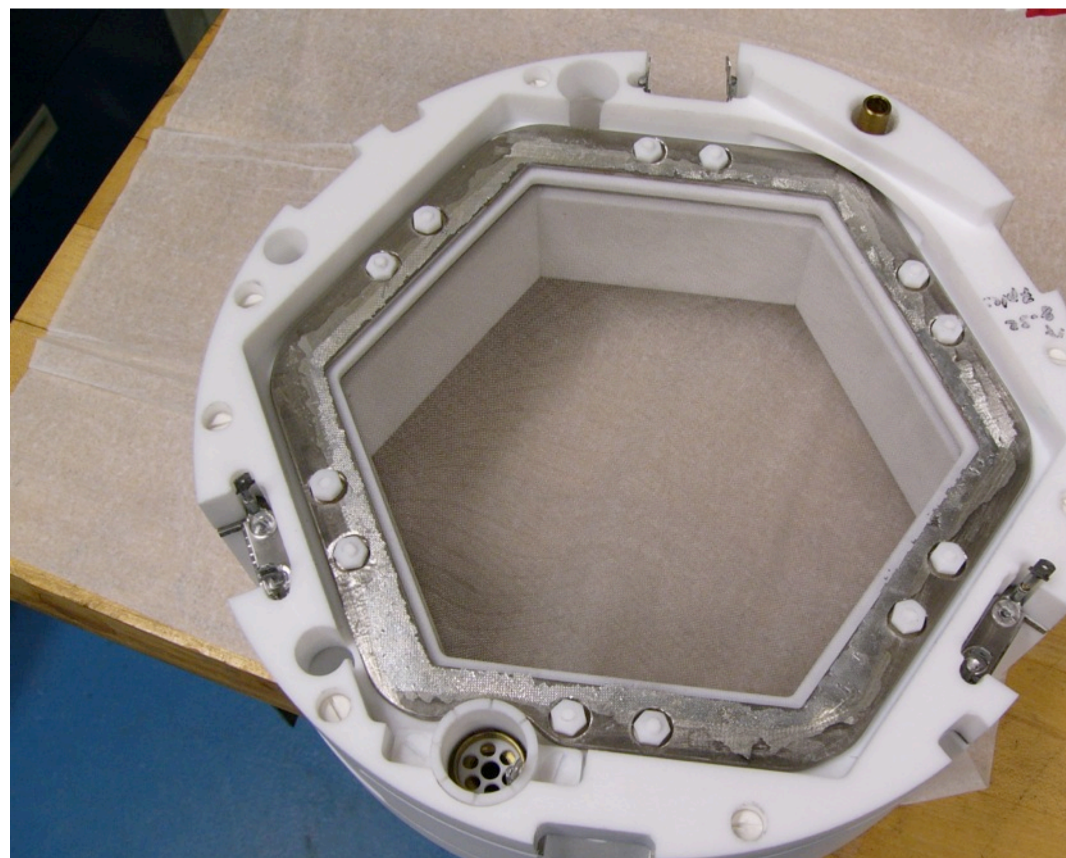
er cathode voltage means higher drift field, and more charge extracted from tracks
er drift field means better electron recoil discrimination, by suppressing recombina
by better isolating the ionization/atomic excitation ratio, which is different for ele
uclear recoils.
X we see 99.6% discrimination at 181/cm.
er drift field is expected to improve discrimination, reducing backgrounds from pp-
inos, Kr-85, Rn daughters, and gamma rays.



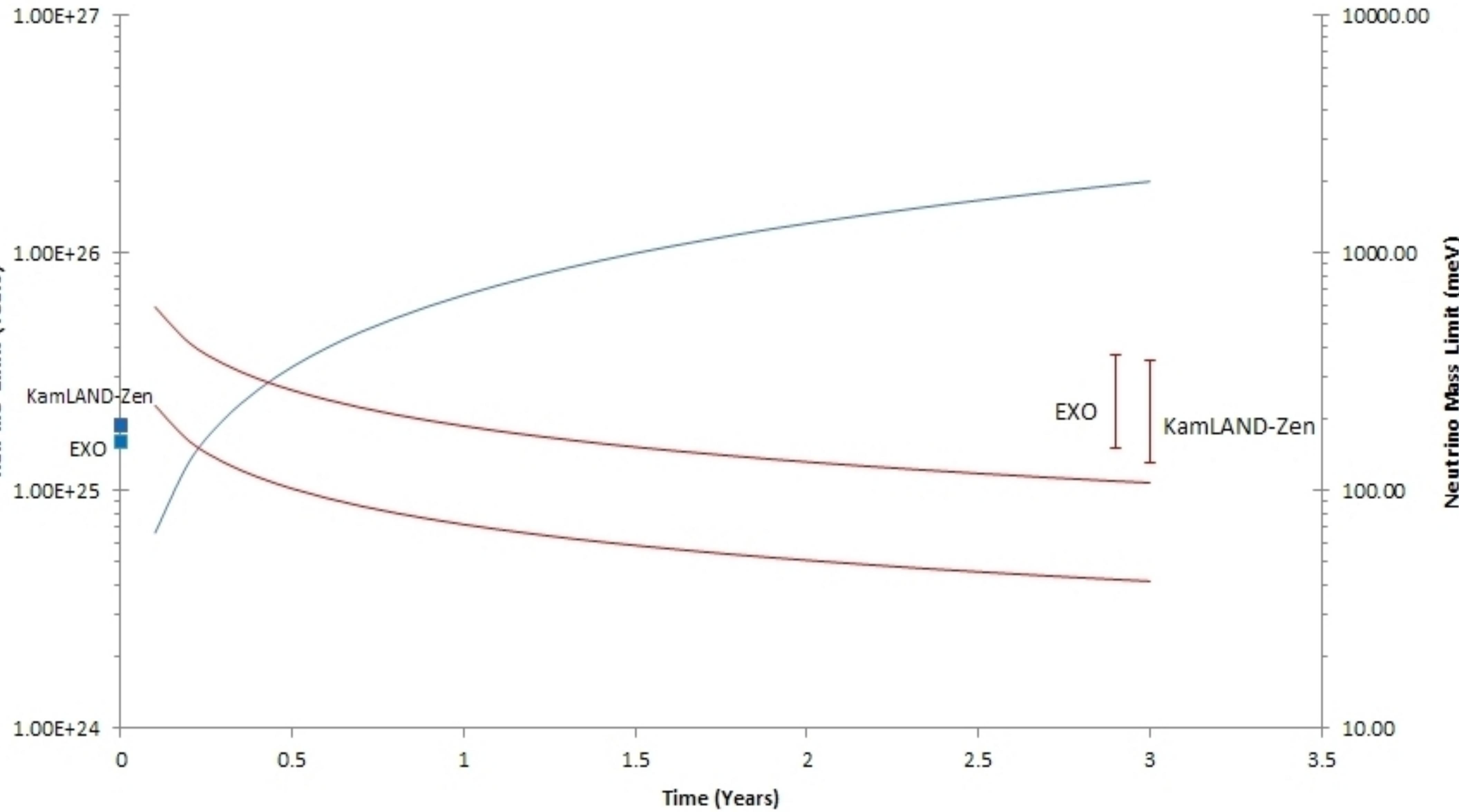


- Currently supported by DHS Academic Research Instrumentation program: $400k/year.
- Two-phase Xe detector; 4 kg active xenon volume.
- Designed for optimal light collection and strong drif
- Currently operating at Yale.
- R&D platform for studying
  - Gamma-neutron (a.k.a. beta-WIMP) discrimina
  - Energy resolution (relevant for neutrinoless DE
  - Calibration with gaseous sources
  - Gamma ray imaging





LZ Expected Performance Over 3 years



ter 3 years of operation, half-life limit is 1.99 x 10^{26} years

has made a WIMP Search run of 86 live-days and released the analysis + PRL submission within 9
nths of first cooling in Davis Lab

kgrounds as expected, inner fiducial ER rate <2 events/day in region of interest

or advances in calibration techniques including ^{83m}Kr and Tritiated-CH_4 injected directly into Xe target

y low energy threshold achieved 3 keVnr with no ambiguous/leakage events

ejection shown to be 99.6+/-0.1% in energy range of interest

rmediate and High Mass WIMPs

nded sensitivity over existing experiments by x3 at 35 GeV and x2 at 1000 GeV

y Mass WIMP Favored Hypotheses ruled out

WIMP Sensitivity 20x better than XENON100

does not observe 6-10 GeV WIMPs hinted at by earlier experiments

re LUX analyses underway or under consideration

In situ calibration using a monoenergetic neutron beam

Improved limits at low WIMP mass, using new calibration data

Impact of LUX data on other WIMP interaction models (spin-dependent, plus larger set of operators)

Solar and galactic axion searches

Neutrino magnetic moment search

Etc… (anything that benefits from low background + low threshold)

LZ Detector is being designed

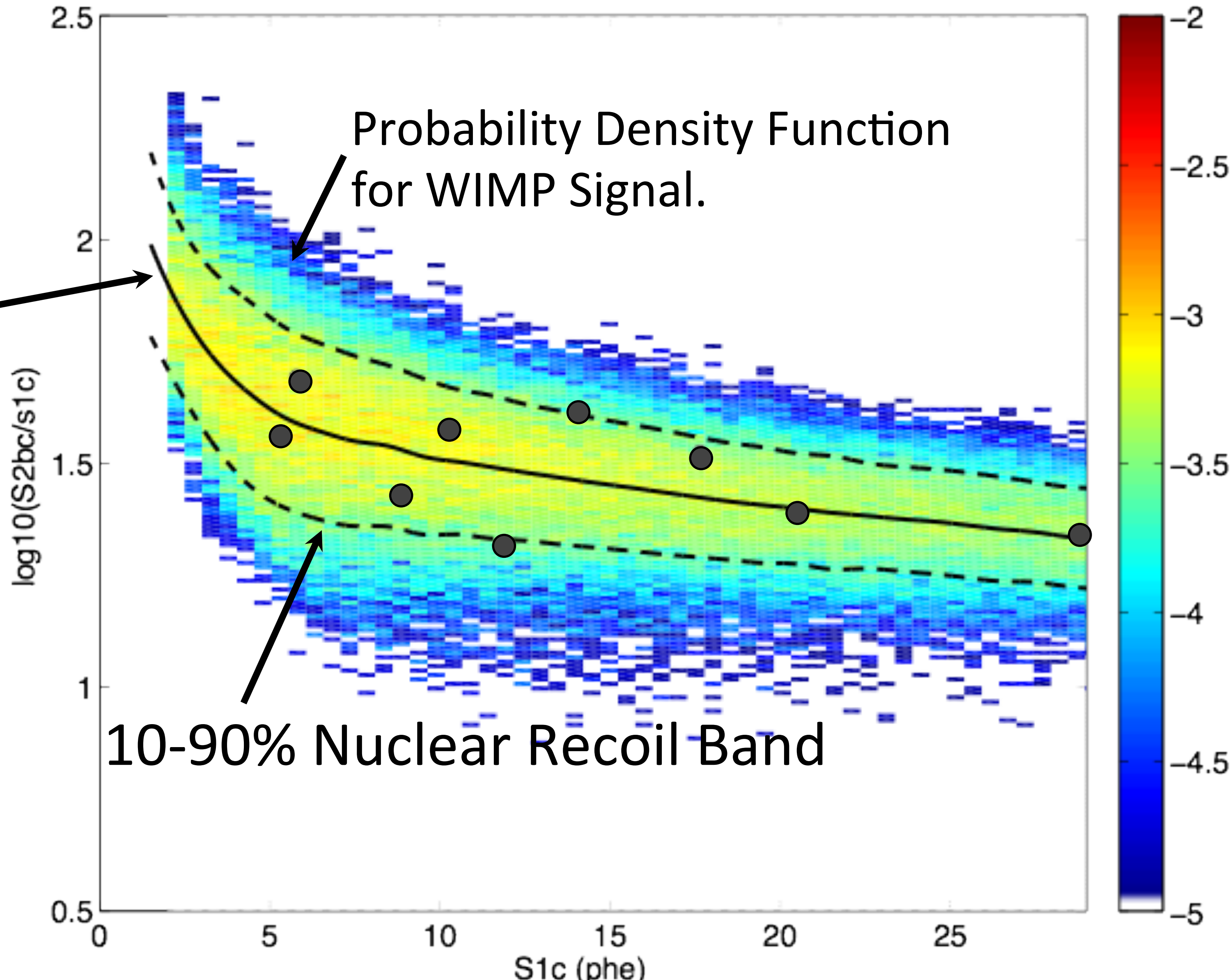
Projected sensitivity 1000 times better than LUX

Will replace LUX in the Davis cavern water tank

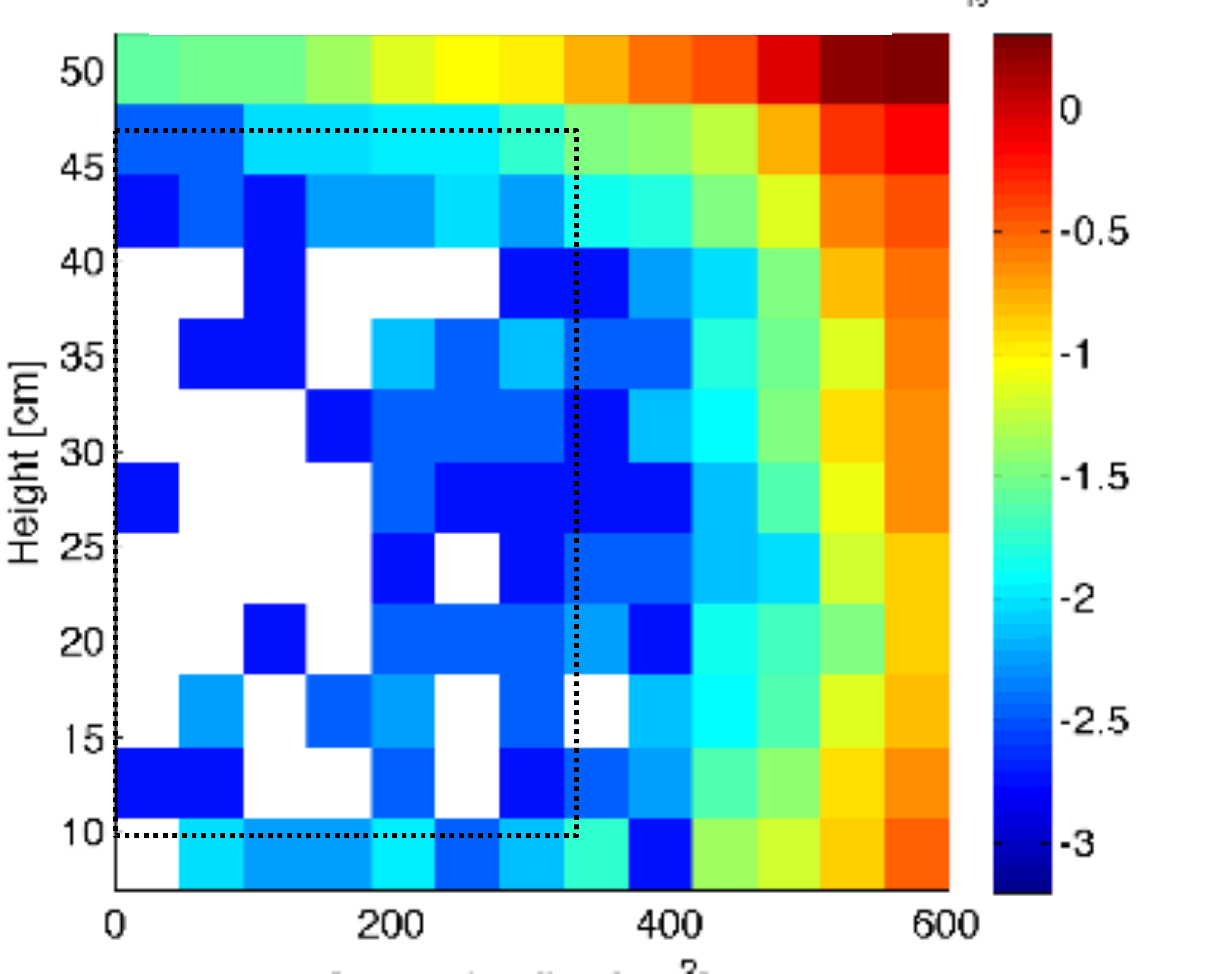
a mass of 1000 GeV and cross section at the existing XENON10
CL Sensitivity 1.9 x 10^{-44} cm^2 - Would expect 9 WIMPs in LUX S

tively
no

d for
3 keVnr
lowest
or
R
on is
.



umes Standard Milky Way Halo parameters as described in Savage, Fr
o (2006) v_0=220 km/s, v_{escape} = 544 km/s, ρ_0 = 0.3 GeV/c^2, v_{earth} = 245 k

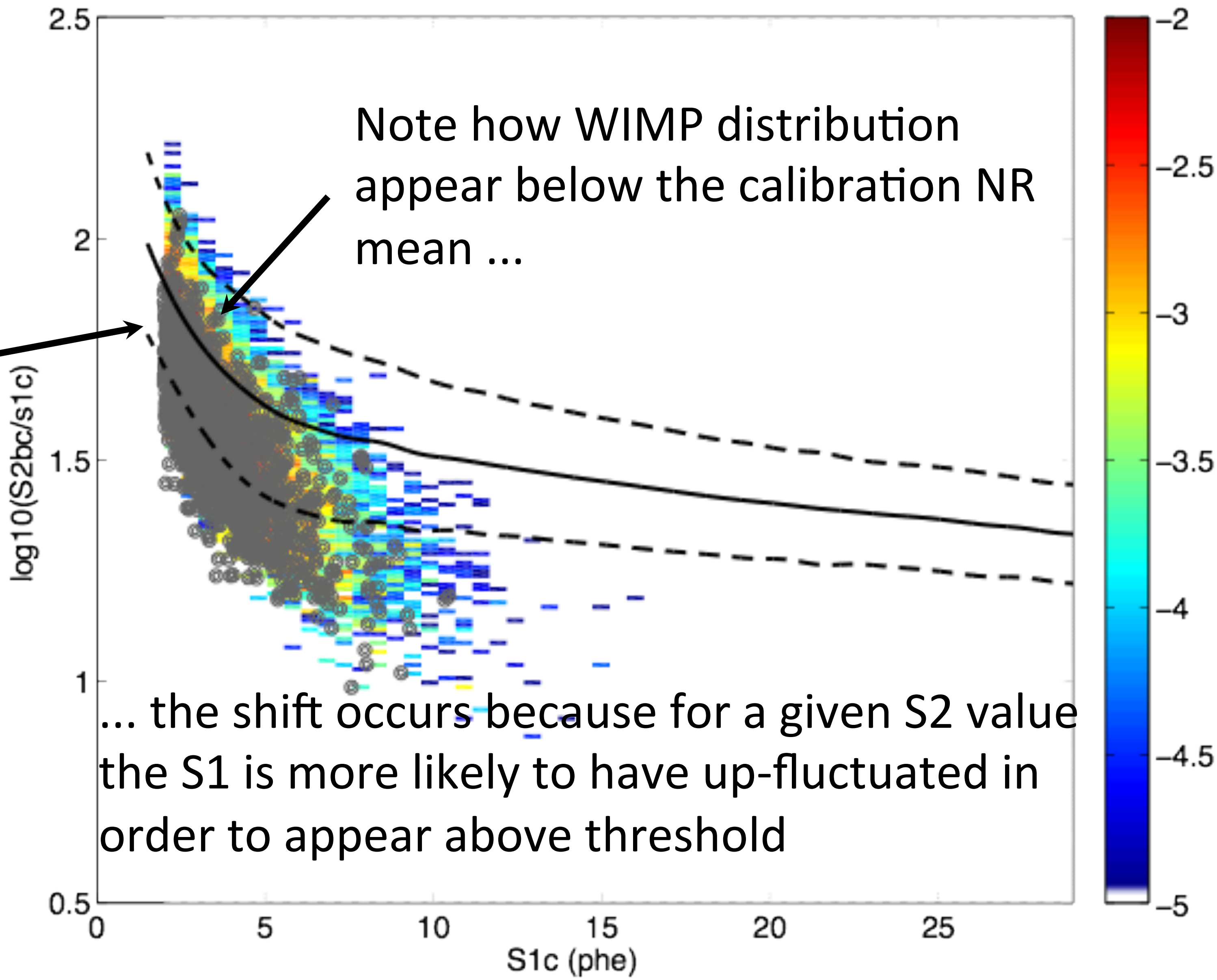


Height [cm]
50
45
40
35
30
25
20
15
10
0
200
400
600
0
-0.5
-1
-1.5
-2
-2.5
-3

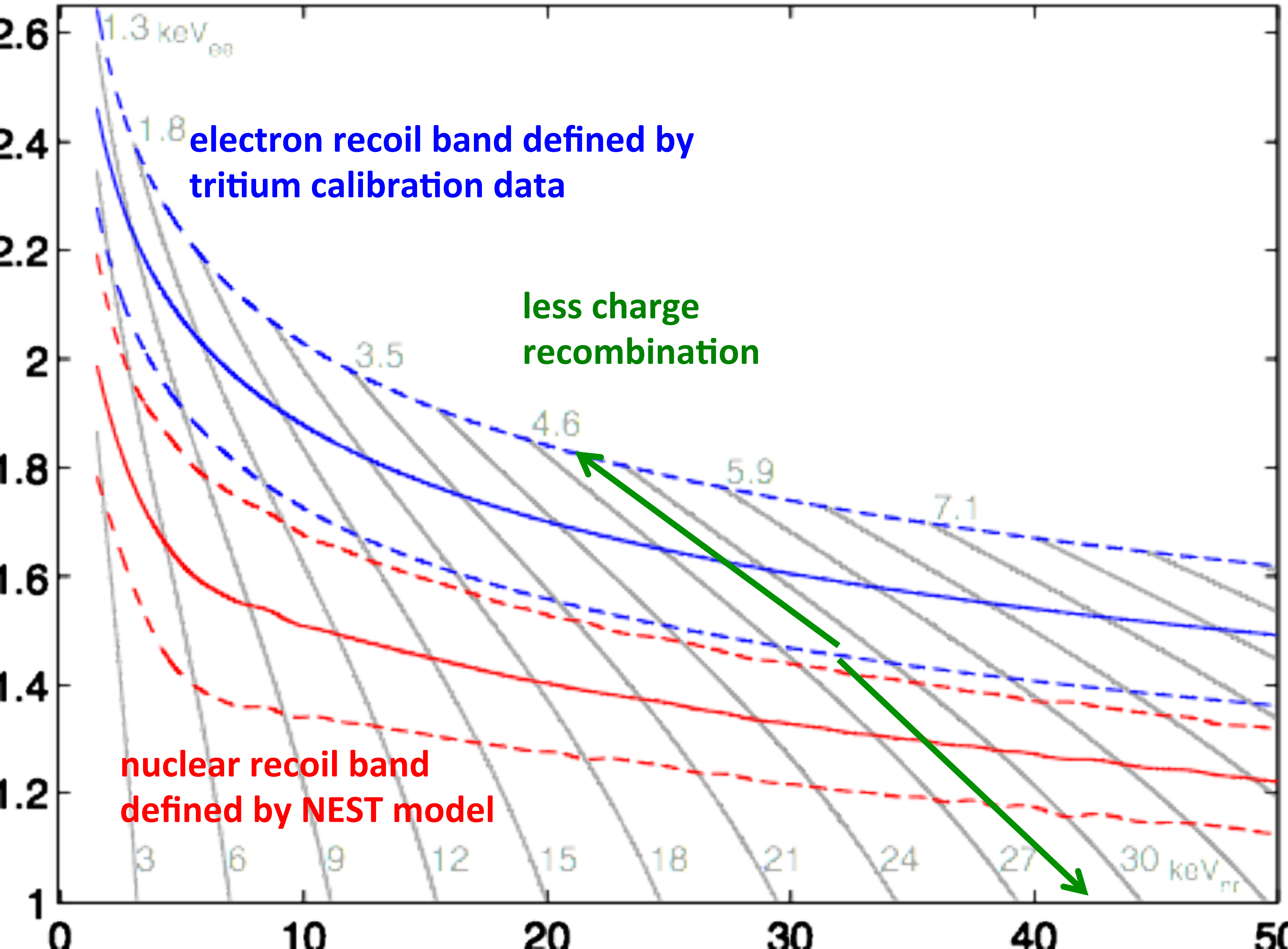
mass of 8.6 GeV and cross section favored CDMS II Si (2012) c
on 2.0 x 10^{-41} cm^2 - Expect 1550 WIMPs in LUX Search

atively
no

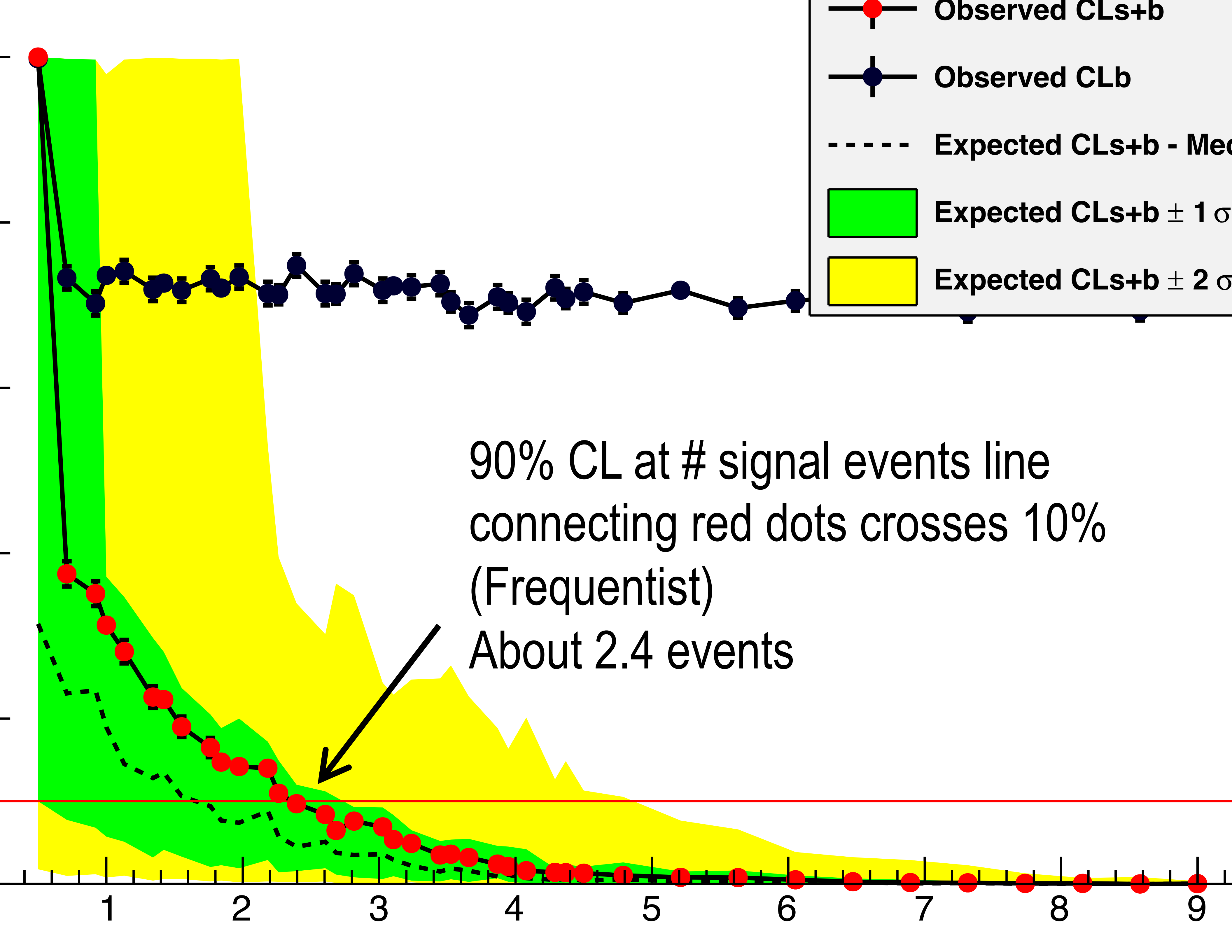
ed for
3 keVnr
t lowest
or
R
on is
e.



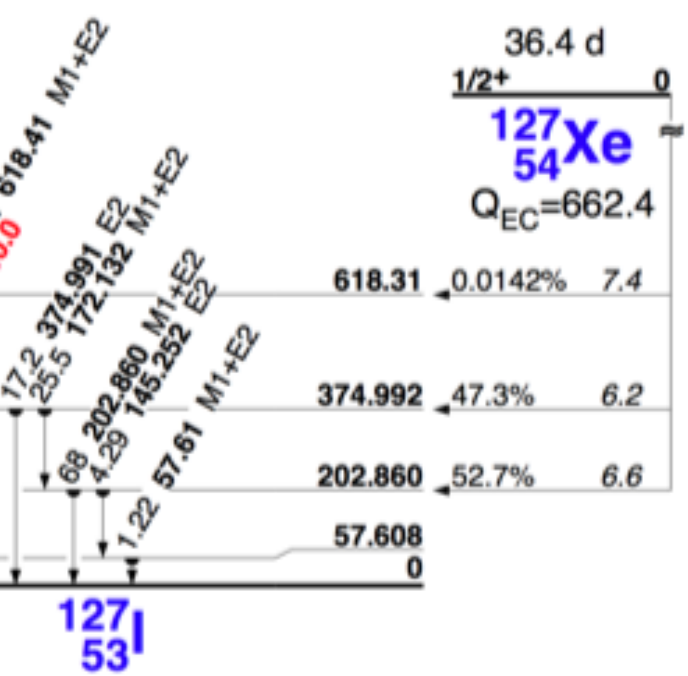
in the WIMP PDF downwards improves the effective ER event leakage fraction

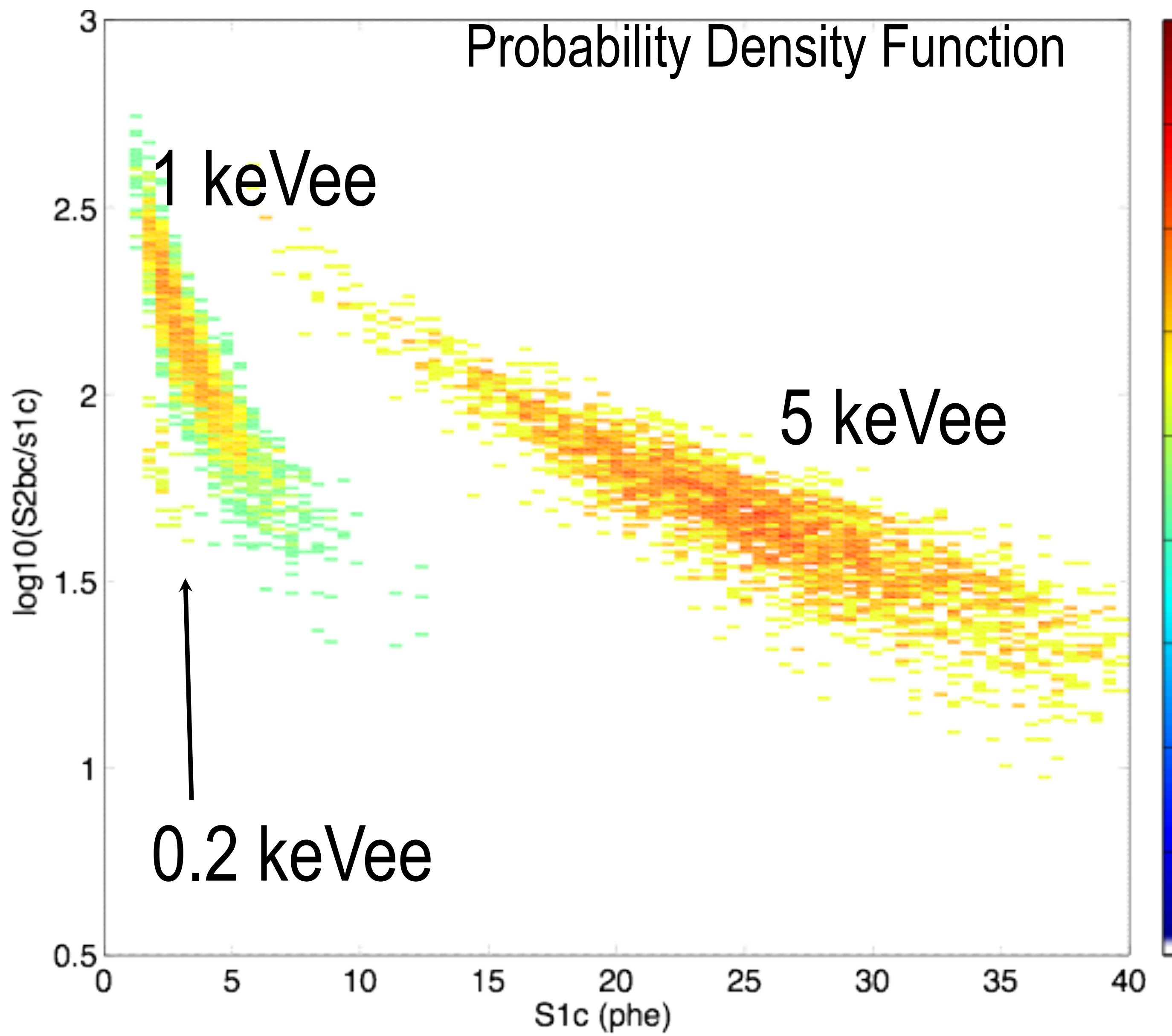


1.3 keV$_{ee}$
1.8
3.5
4.6
5.9
7.1
electron recoil band defined by tritium calibration data
less charge recombination
nuclear recoil band defined by NEST model
3
6
9
12
15
18
21
24
27
30 keV$_{nr}$
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0
10
20
30
40
50

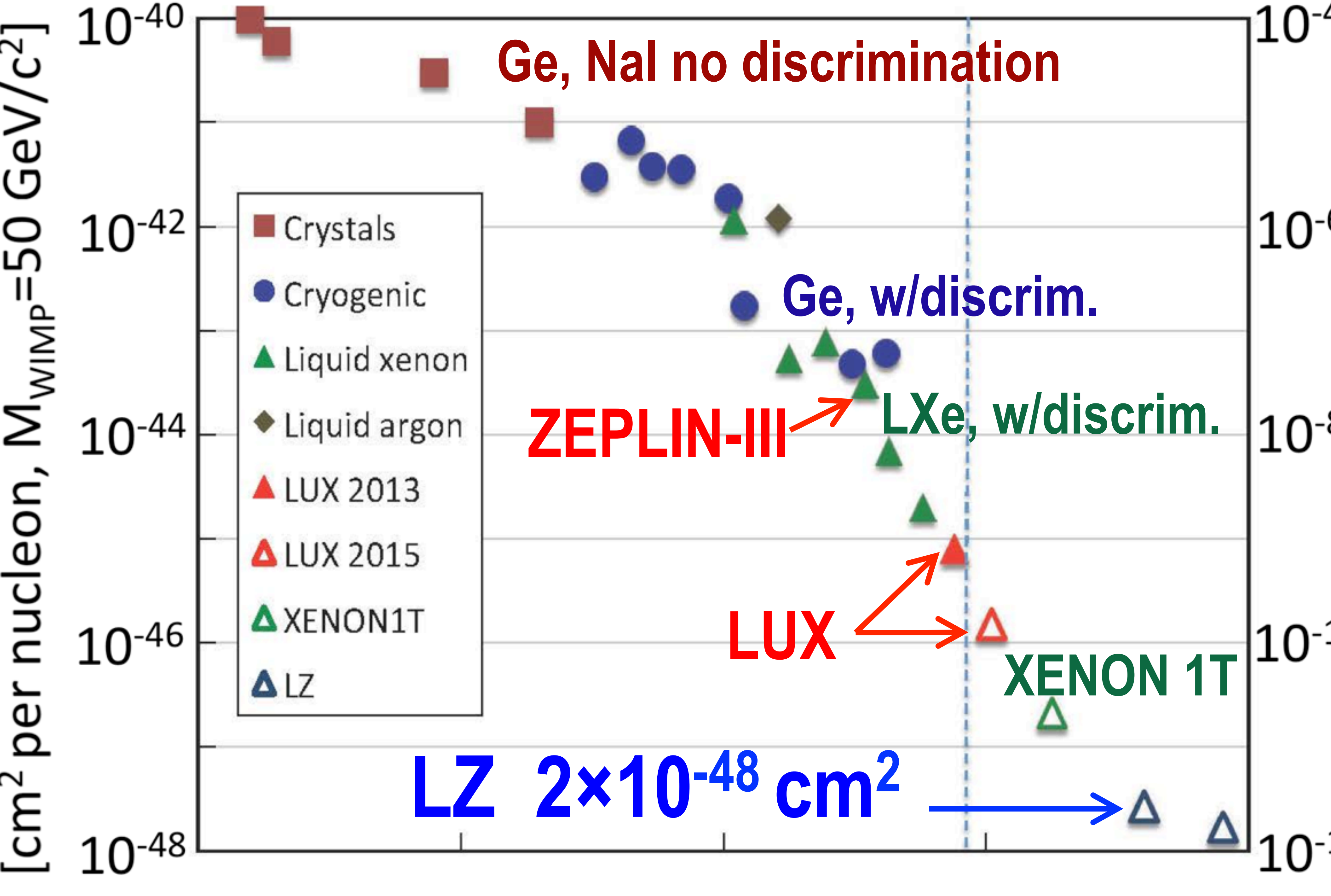

Observed CLs+b
Observed CLb
Expected CLs+b - Med
Expected CLs+b ± 1 σ
Expected CLs+b ± 2 σ
90% CL at # signal events line
connecting red dots crosses 10%
(Frequentist)
About 2.4 events
1
2
3
4
5
6
7
8
9

line emission in center of detector following full escape of ga
ciated with nuclear excited state





Time Evolution

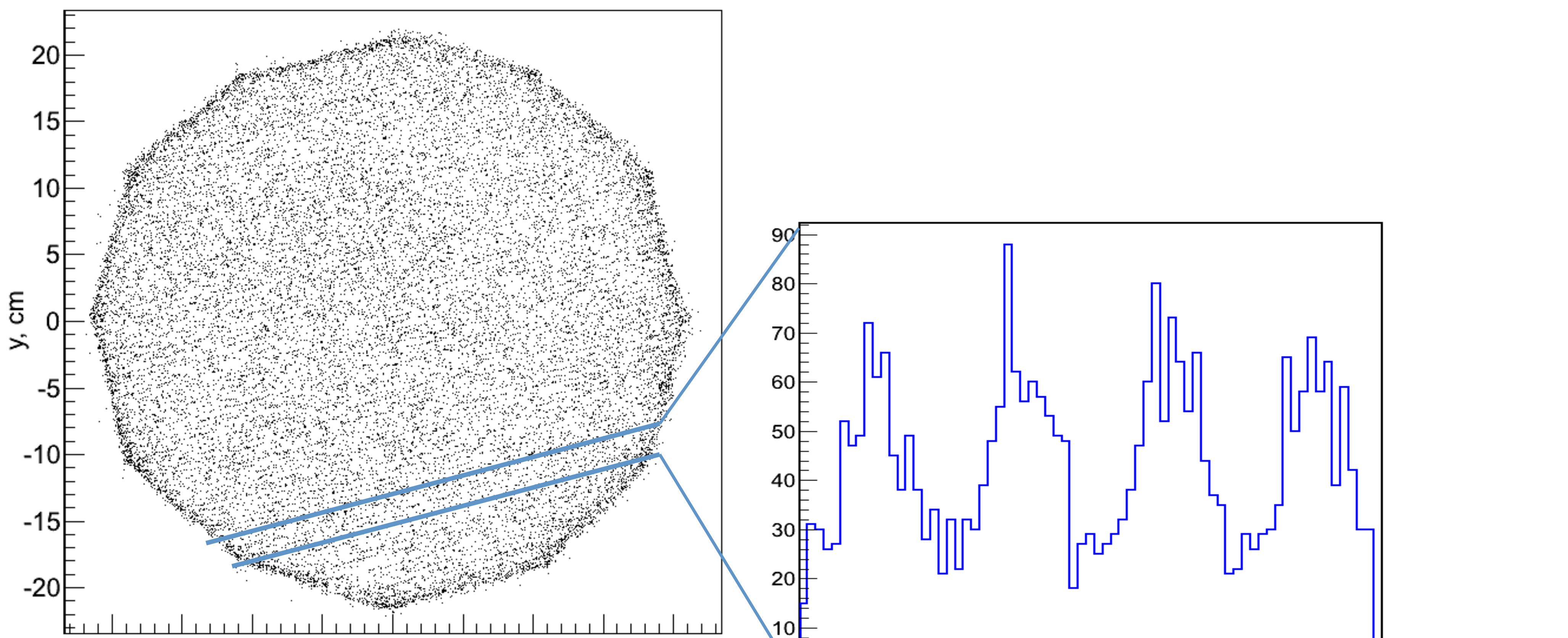


ate is determined by the time between S1 and S2
drift speed of 1.51 mm/microsecond)

ponse Functions (LRFs) are found by iteratively fitting the distribution
al for each PMT.

n is determined by fitting the S2 hit pattern relative to the LRFs.

uction of XY from alpha events near the anode grid resolves grid wires with 5 mm p



(or, how did you spend your summer?)

ril 21 - August 8, 2013 - 110 calendar days

.3 live days of WIMP Search

8.3+/-6.5 kg fiducial mass

librations

equent injected ^{83m}Kr calibration to correct for any S1 or S2 gain shifts

nBe&Cf calibrations+Sims to define NR band

ected Tritiated Methane defines full ER band at all relevant energies

ficiency

ficiency for WIMP event detection was studied using data from
libration sets using multiple techniques and all were all shown to be
nsistent with one another

ta Analysis and Blinding

e Xe Target inner fiducial volume is very simple, it sits inside a larger volume of Xe th only a “virtual” surface dividing them

odeling of extrinsic and intrinsic background signals in large monolithic Xe volume has low system

blinding was imposed for the first WIMP data analysis

e aimed to apply minimum set of cuts in order to reduce any tuning of event cuts/acceptance.

he cuts list is very short ...

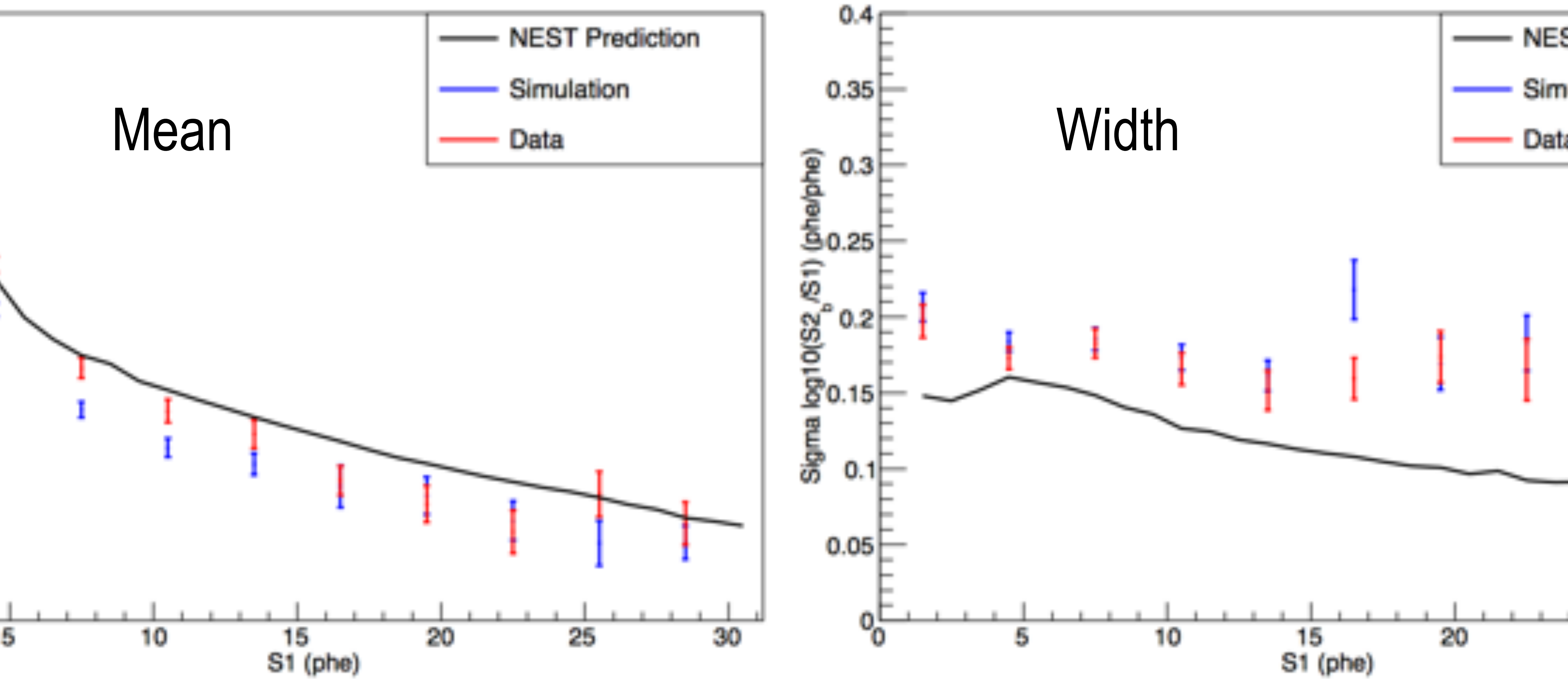
ucial Volume was selected based on requirement to keep low energy events from d and teflon surface out of WS data. Primarily alpha-decay events.

w energy alpha-parent nuclear recoil events generate small S2 + S1 events. Studies position construction resolution. Tested using data outside WIMP search S1 energy range. This ensured tha osition reconstruction for sets were similar, and definition of fiducial was not biased.

e of Profile Likelihood Ratio (PLR) analysis means we don’t have to draw acceptar xes

is avoids potential bias in data analysis from selecting regions in S1,S2 signal-space

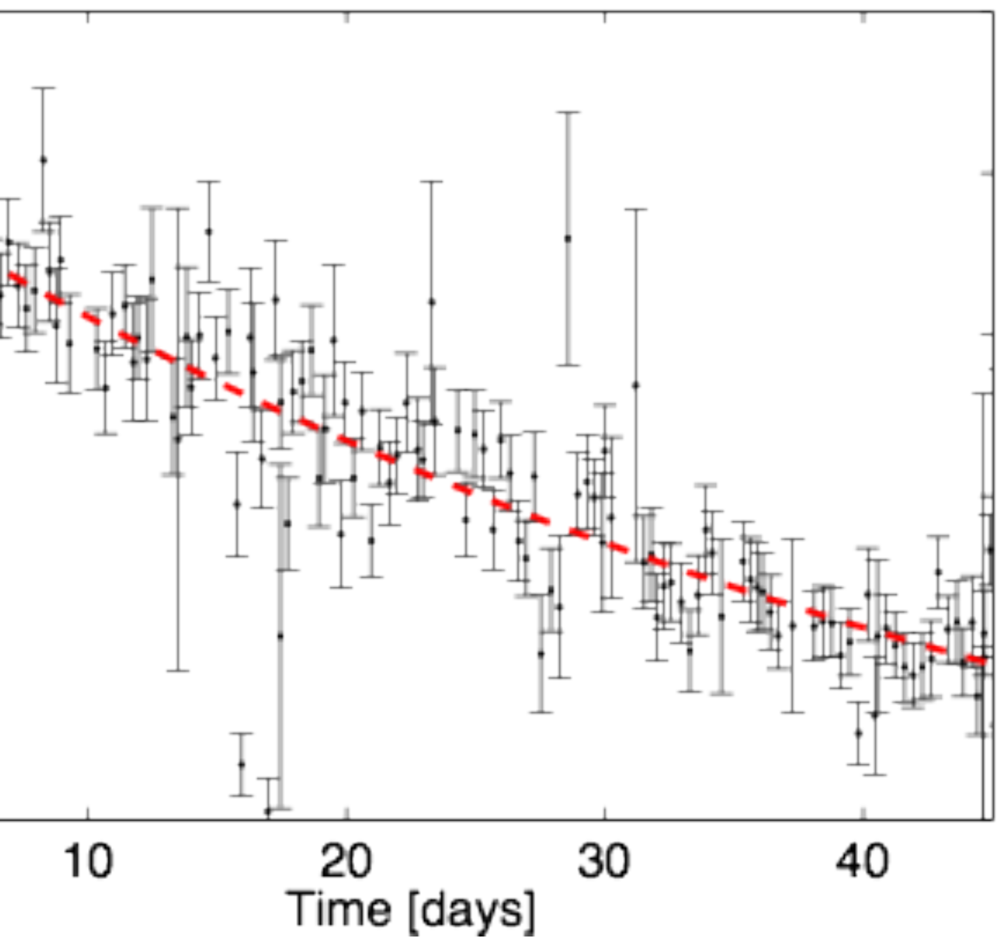
outs for Profile Likelihood Ratio analysis were developed using high statistics in situ ibrations, with some simulations to cross check



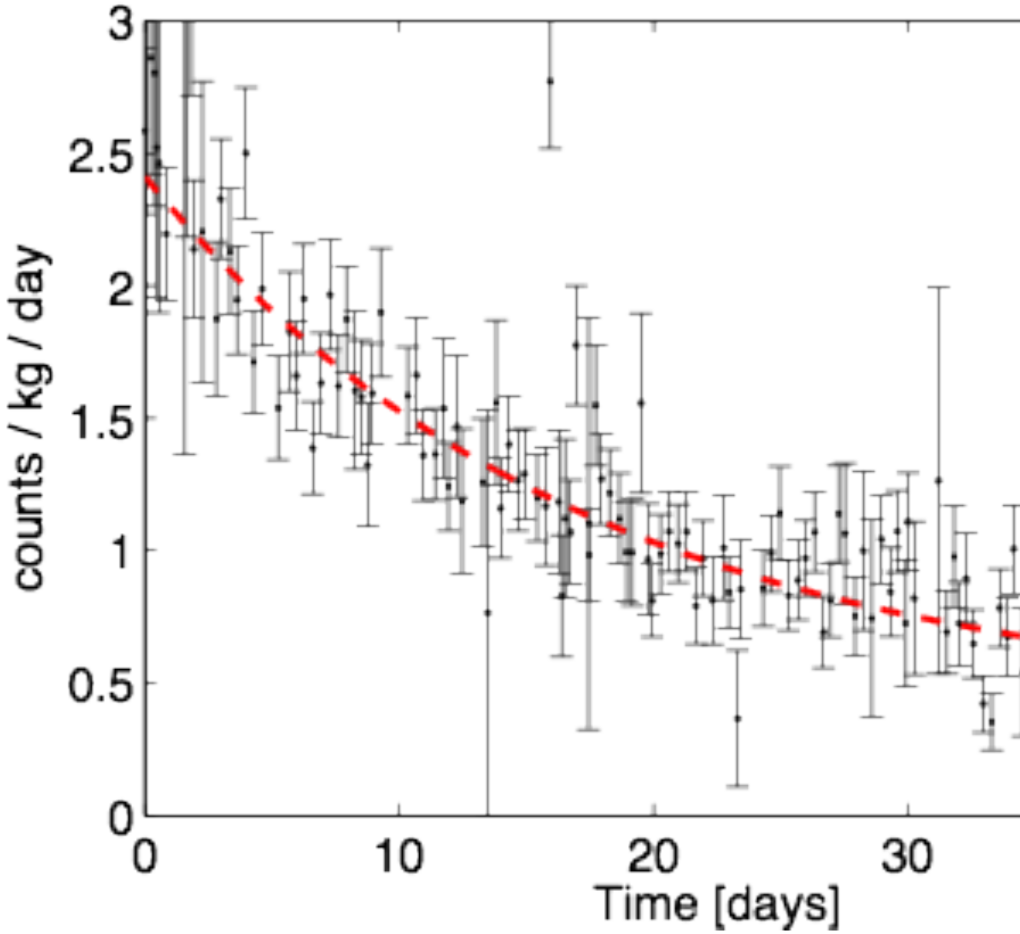
- Above plots show comparisons between simulation (blue), the NEST prediction (black), and data for the mean and width of the nuclear recoil band from AmBe calibrations
- The mean and width are different in the calibrations because the data contain ER contamination and neutron-X events, which are modeled well by the

Cosmogenic Isotopes Decaying

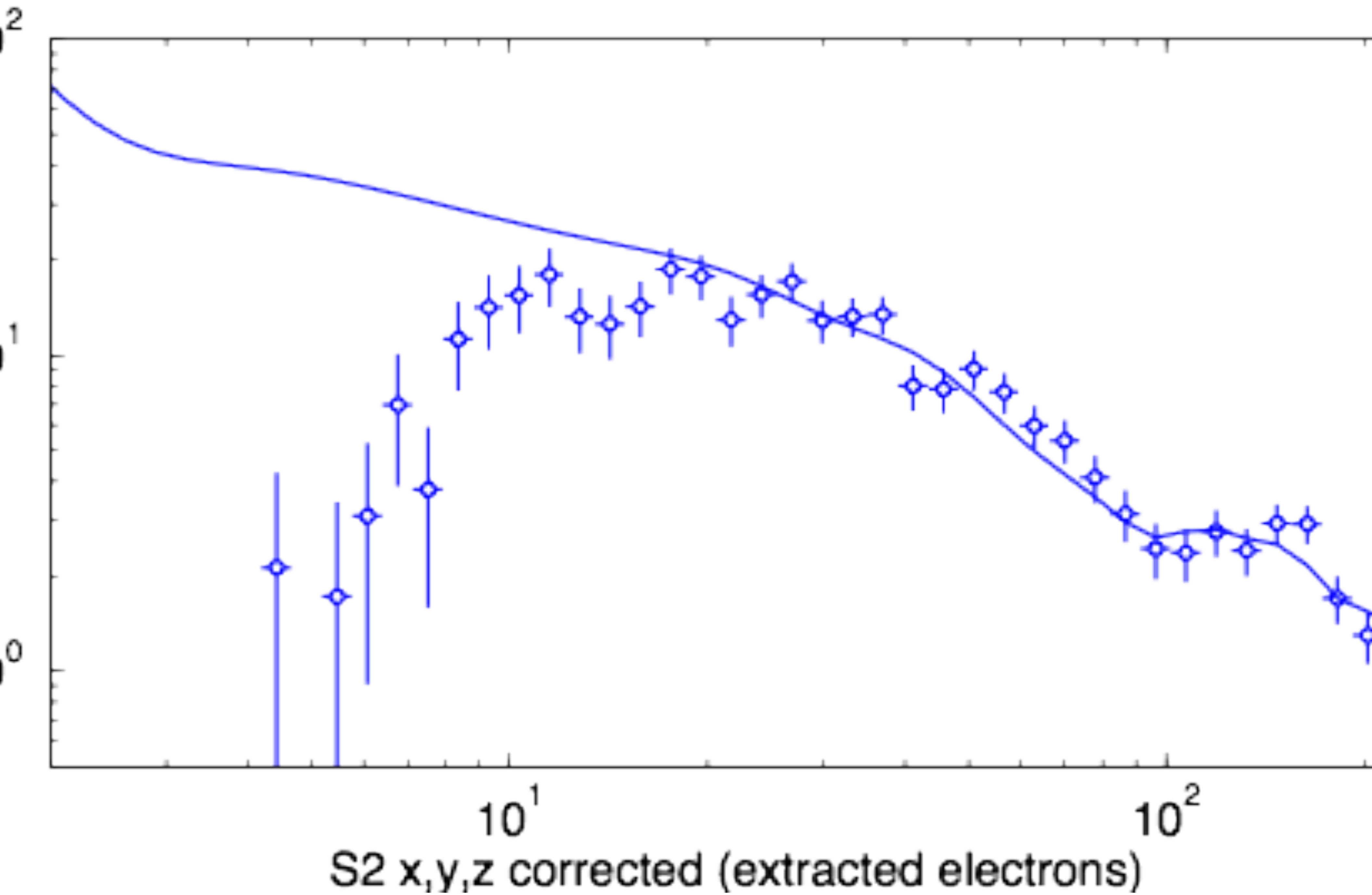
.7Xe Decay vs Time



131mXe Decay vs Time



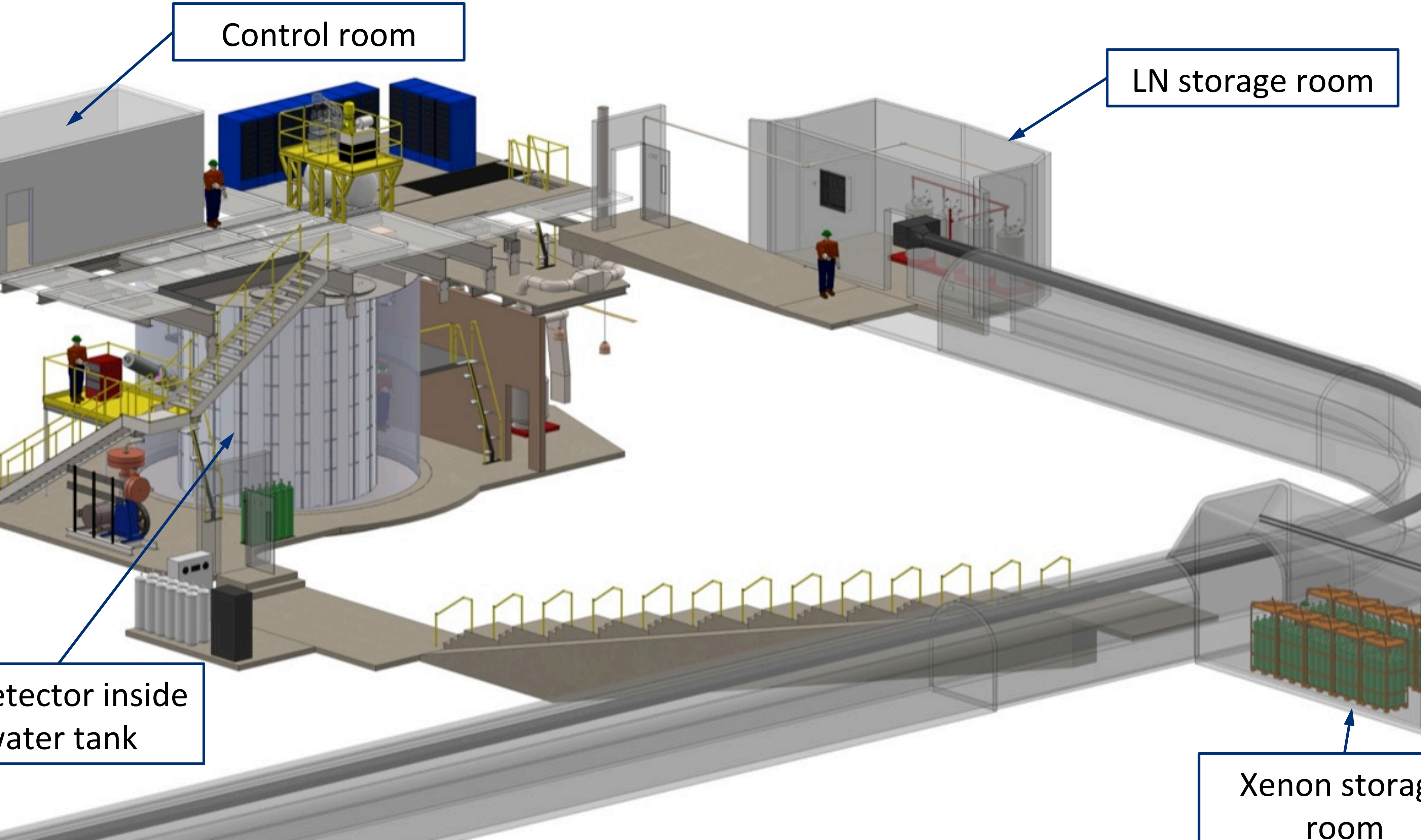
AmBe S2 Calibration



Extra Slides

LZ Underground at SURF

Years of experience at SURF fro



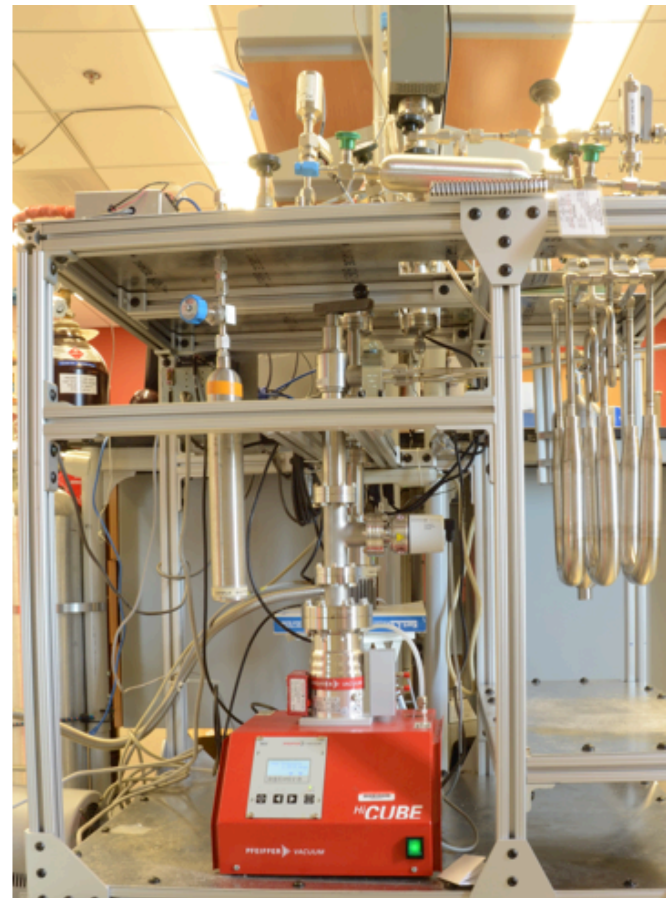
^{85}Kr Removal and Screening

emove Kr to <15 ppq (10^{-15} g/g) using gas chromatography.

est LUX batch 200 ppq

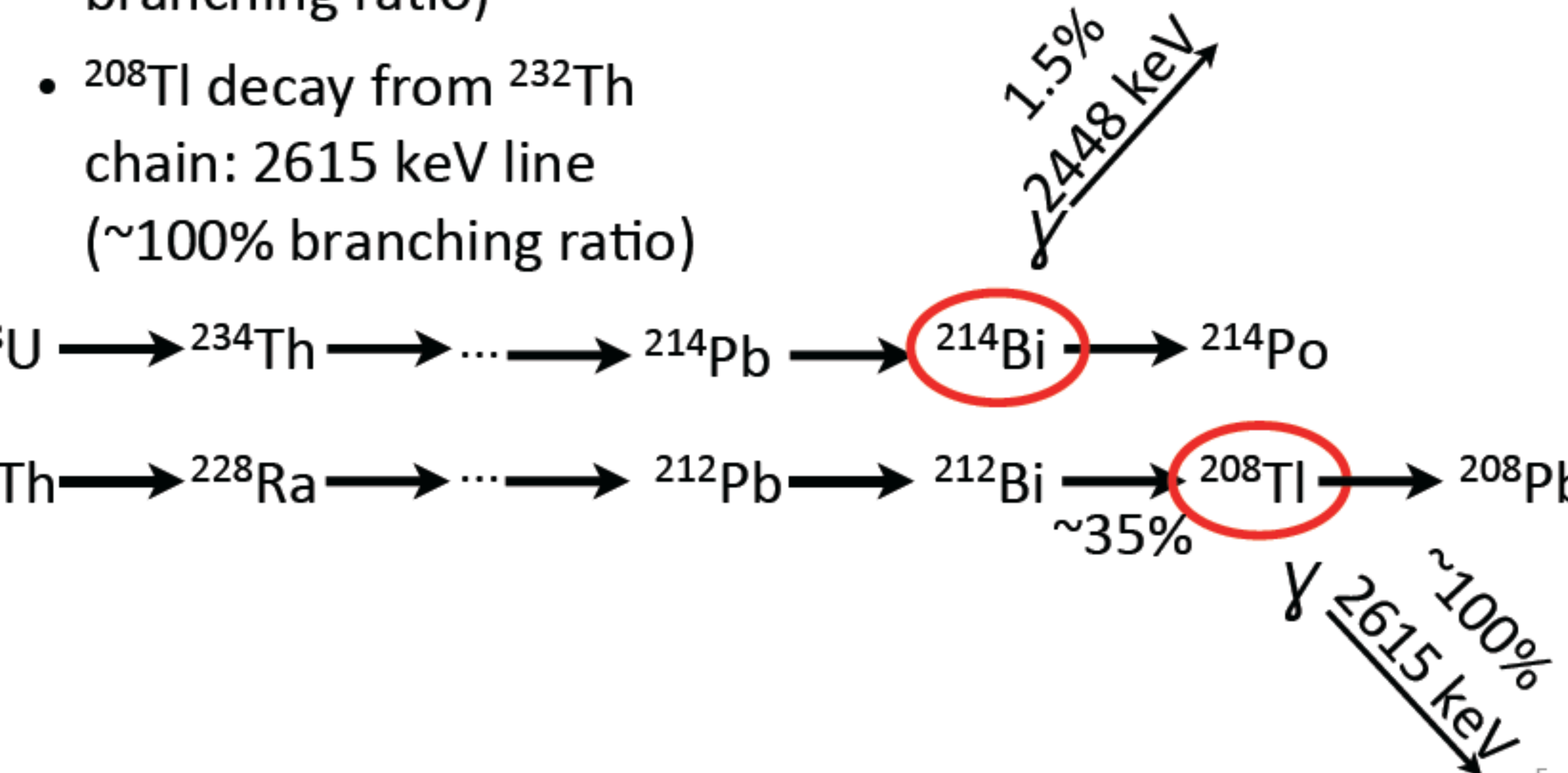
etting up to process 200 kg/day at SLAC

ave a sampling program to instantly assay the removal at SLAC and ontinuously assay in situ



Backgrounds Near 2458 keV

- ^{214}Bi from ^{238}U chain: one line at 2448 keV (1.5% branching ratio)
- ^{208}Tl decay from ^{232}Th chain: 2615 keV line (~100% branching ratio)



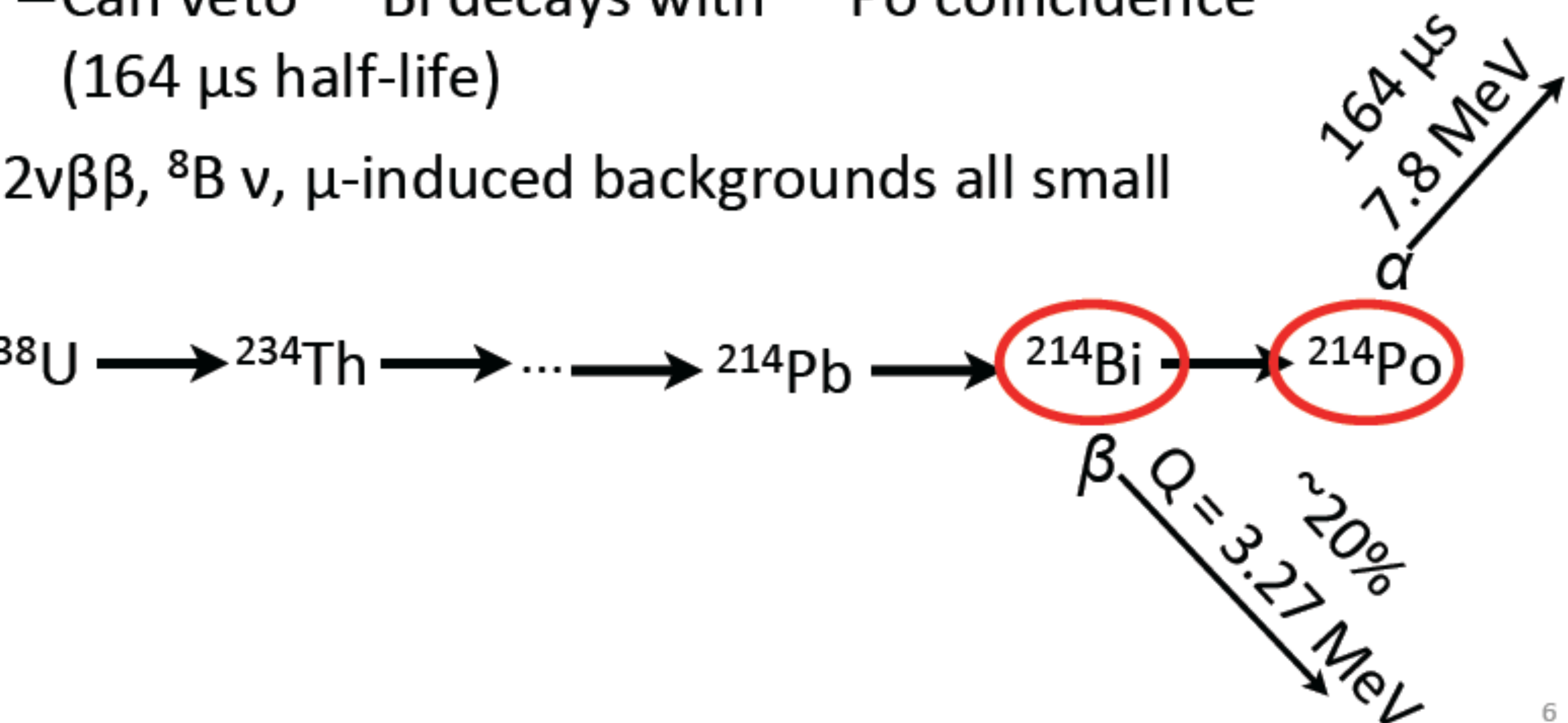
Important Backgrounds

Internal radon not a concern:

– 2448 keV line comes with a beta => self-vetoing

– Can veto ^{214}Bi decays with ^{214}Po coincidence (164 μs half-life)

$2\nu\beta\beta$, ^{8}B ν, μ-induced backgrounds all small



Xe Detector PMTs

- .1410-22 3” PMTs for TPC region
  - Extensive development program, 50 tubes in hand, benefit from similar development for XENON, PANDA-X and RED
  - Materials ordered and radioassays started prior to fabrication.
  - First production tubes early 2016.
  - Joint US and UK effort
- 3520-406 1” for skin region
  - Considering using 2” or 3” for bottom dome region, recycle tubes from older detectors

Xe Detector Prototyping

tensive program of prototype development underway

ree general approaches

Testing in liquid argon, primarily of HV elements, at Yale and soon at L

Design choice and validation in small (few kg) LXe test chambers in ma locations: LLNL, Yale-> UC Berkeley, LBNL, U Michigan, UC Davis, Impe College, MEPhI

System test platform at SLAC, Phase I about 100 kg of LXe, TPC protot testing to begin in few months

Outer Detector

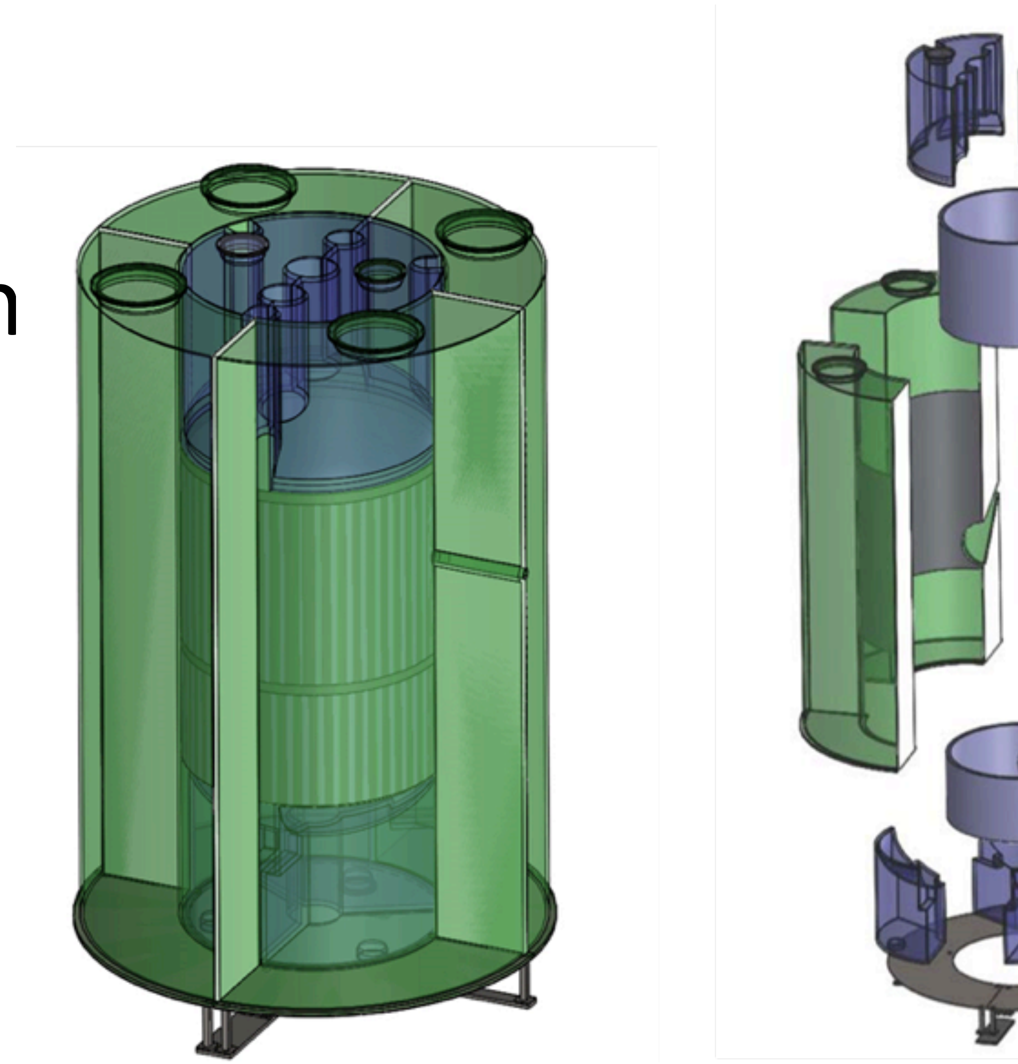
ntial to utilize most Xe,
mize fiducial volume

nented tanks – installation
traints (shaft, water tank)

olinium - loaded
illator, LAB, OK
erground

Bay legacy, scintillator &
s (and people)

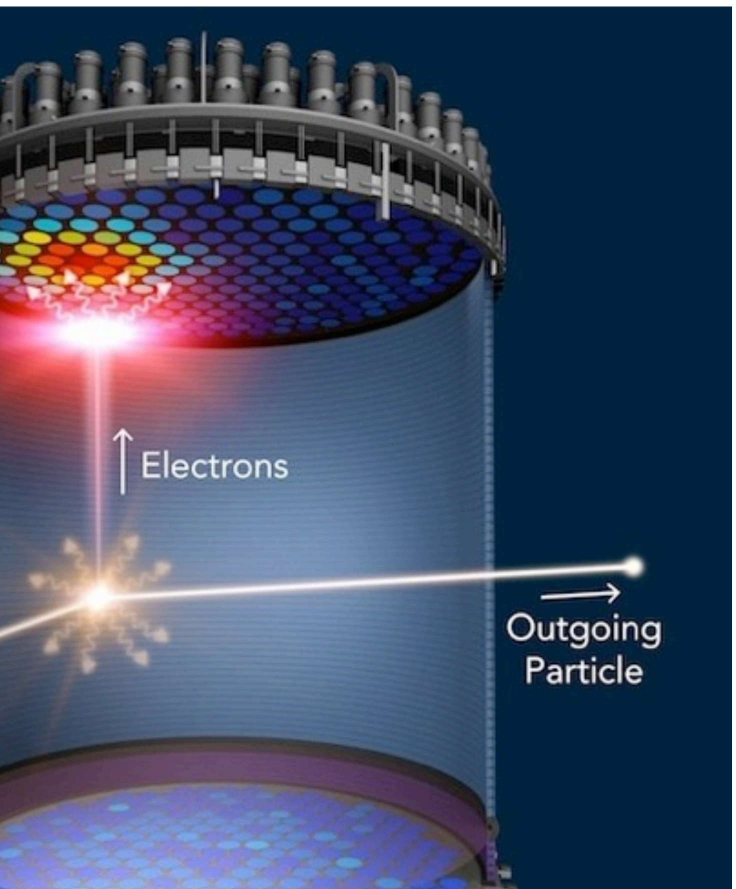
nced conceptual design



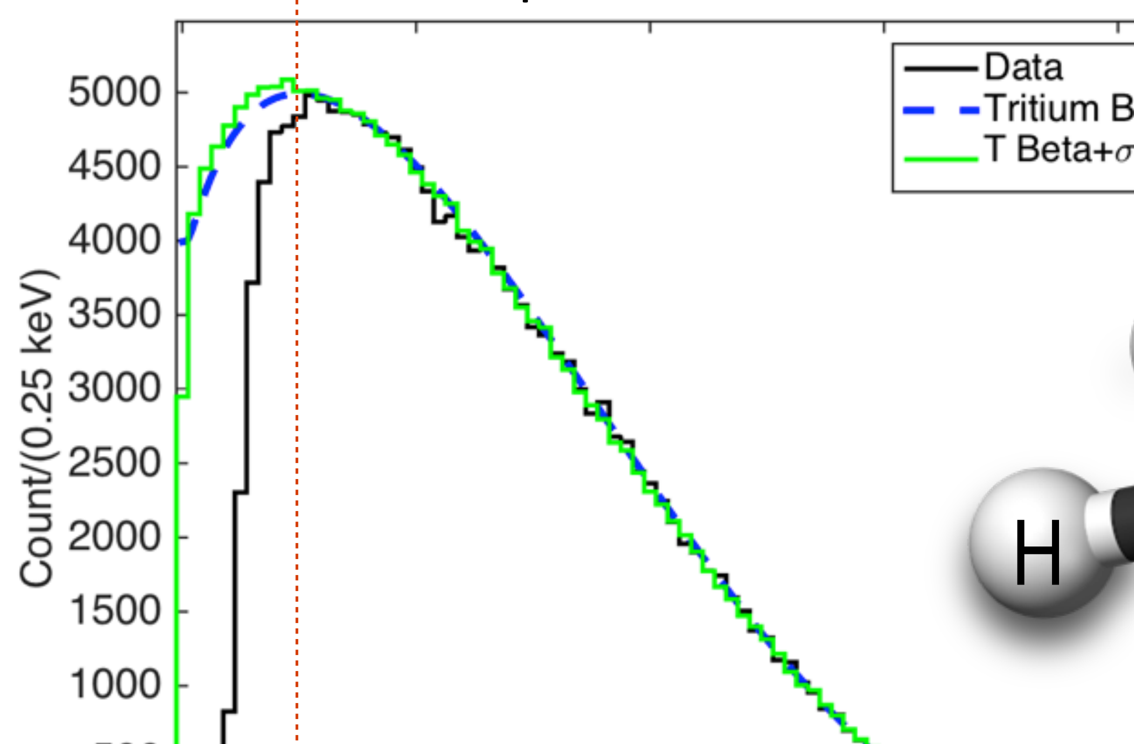
**Layout of the LZ outer detector system, which consists of nine acry
largest are the four quarter-tanks on the sides. Two tanks cover th
the bottom. The exploded view on the right shows the displacer cy
between the acrylic vessels and the cryostat.**

LZ Calibrations

- nonstrated in LUX. Calibrate The Signal and Background Model *in situ.*
- Neutron Generator (Nuclear Recoils)
- ated Methane (Electron Recoils)
- itional Sources e.g. YBe Source for low energy (Nuclear Recoils)

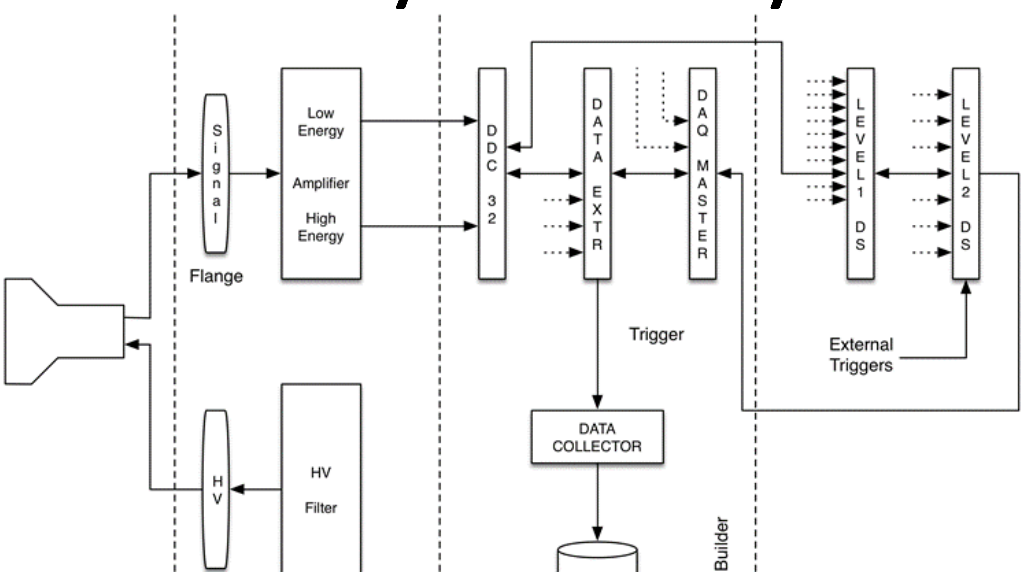


Tritium Beta Spectrum Measured in LU

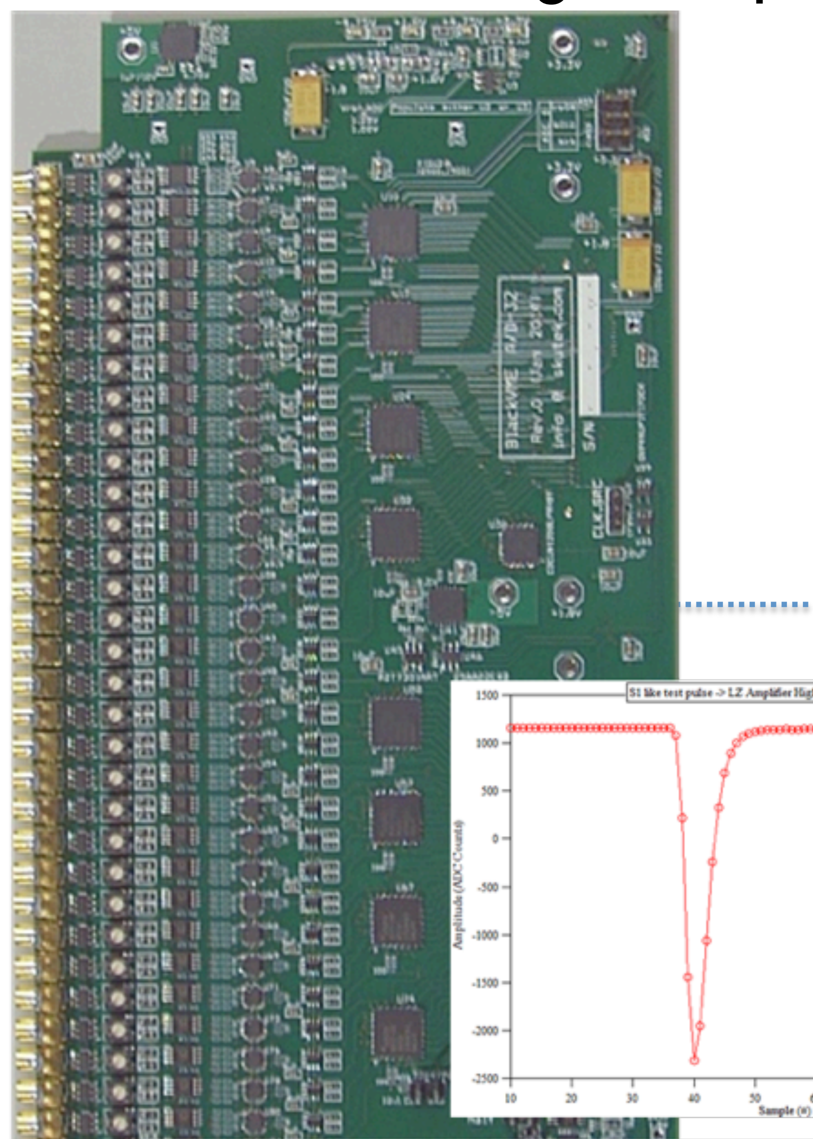


Electronics/DAQ

- UX legacy, augmented by xperienced new groups primarily DAQ, controls)
- rototyping underway, will ad to full – chain test of key ements by end of year



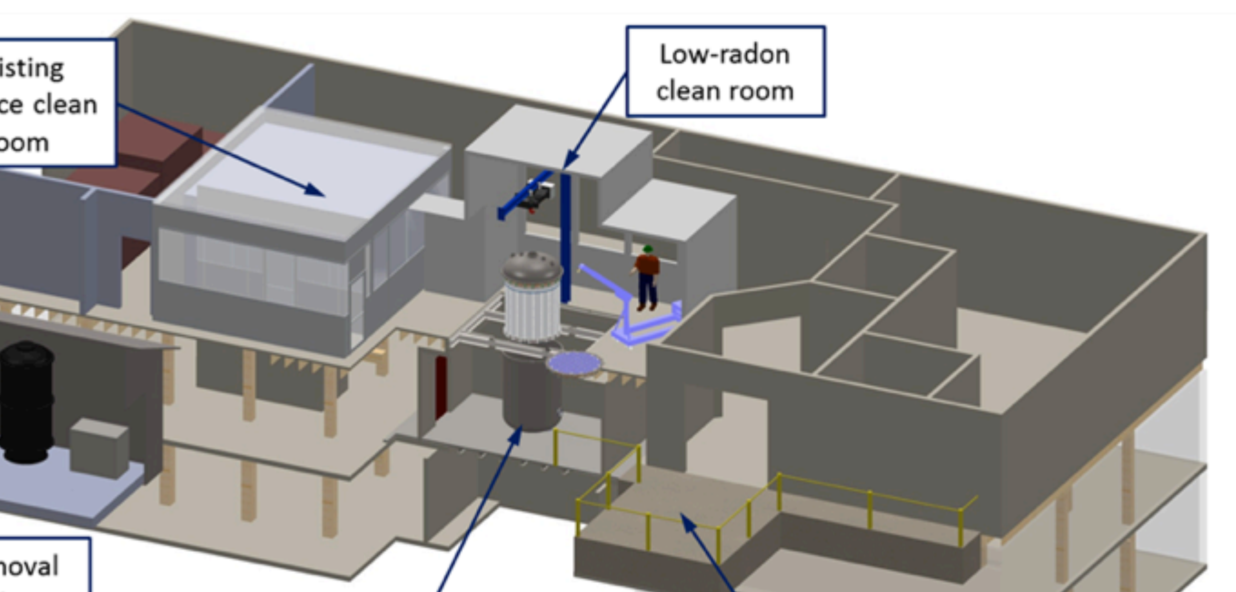
32 channel digitizer pr

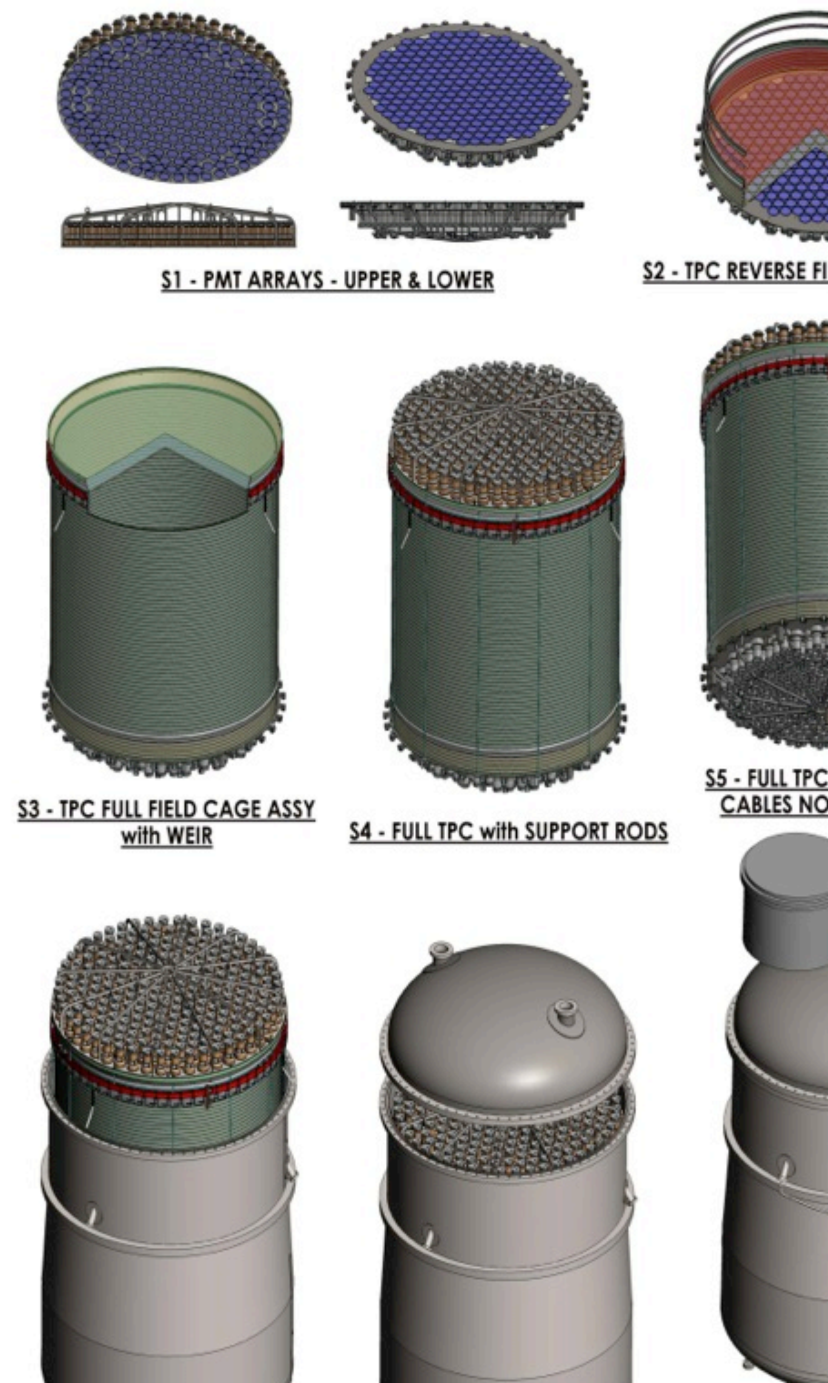


S1 test pulse from the high-gain amplifie

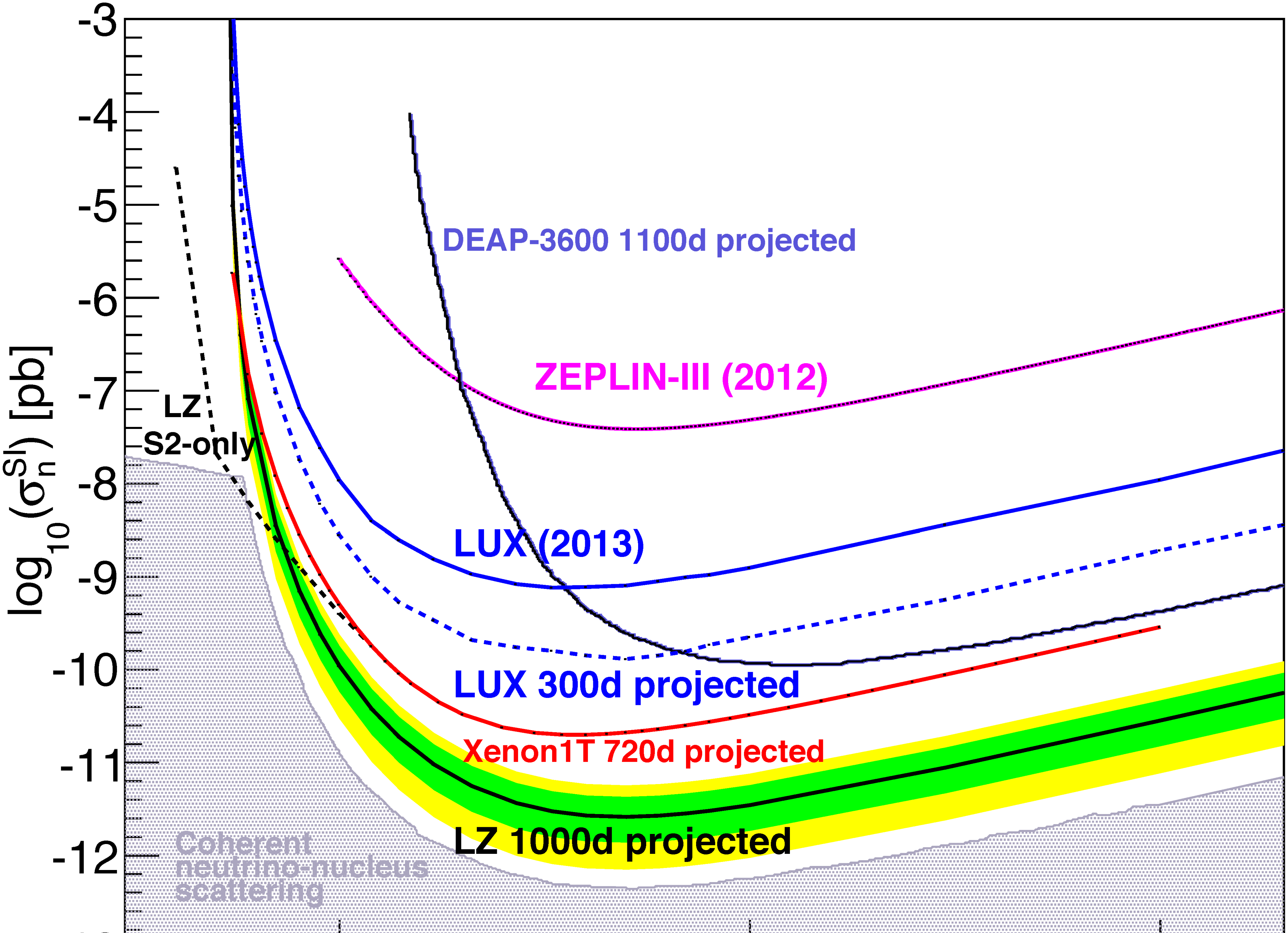
Integration/Installation

- rface assembly of TPC into inner
yostat
- JX experience at SURF
- edicated on – site infrastructure
nprovements for LZ. Design started,
nstruction

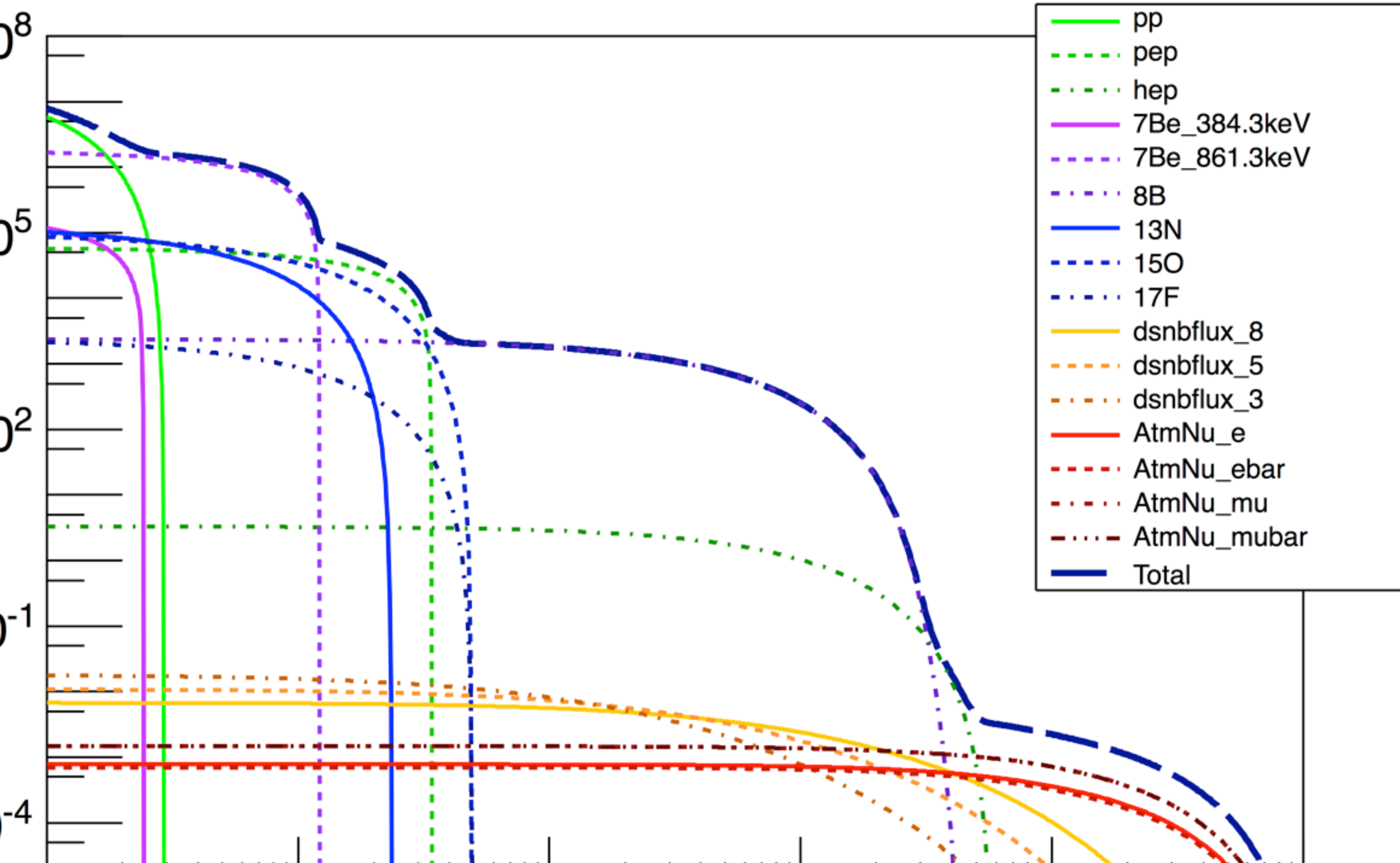




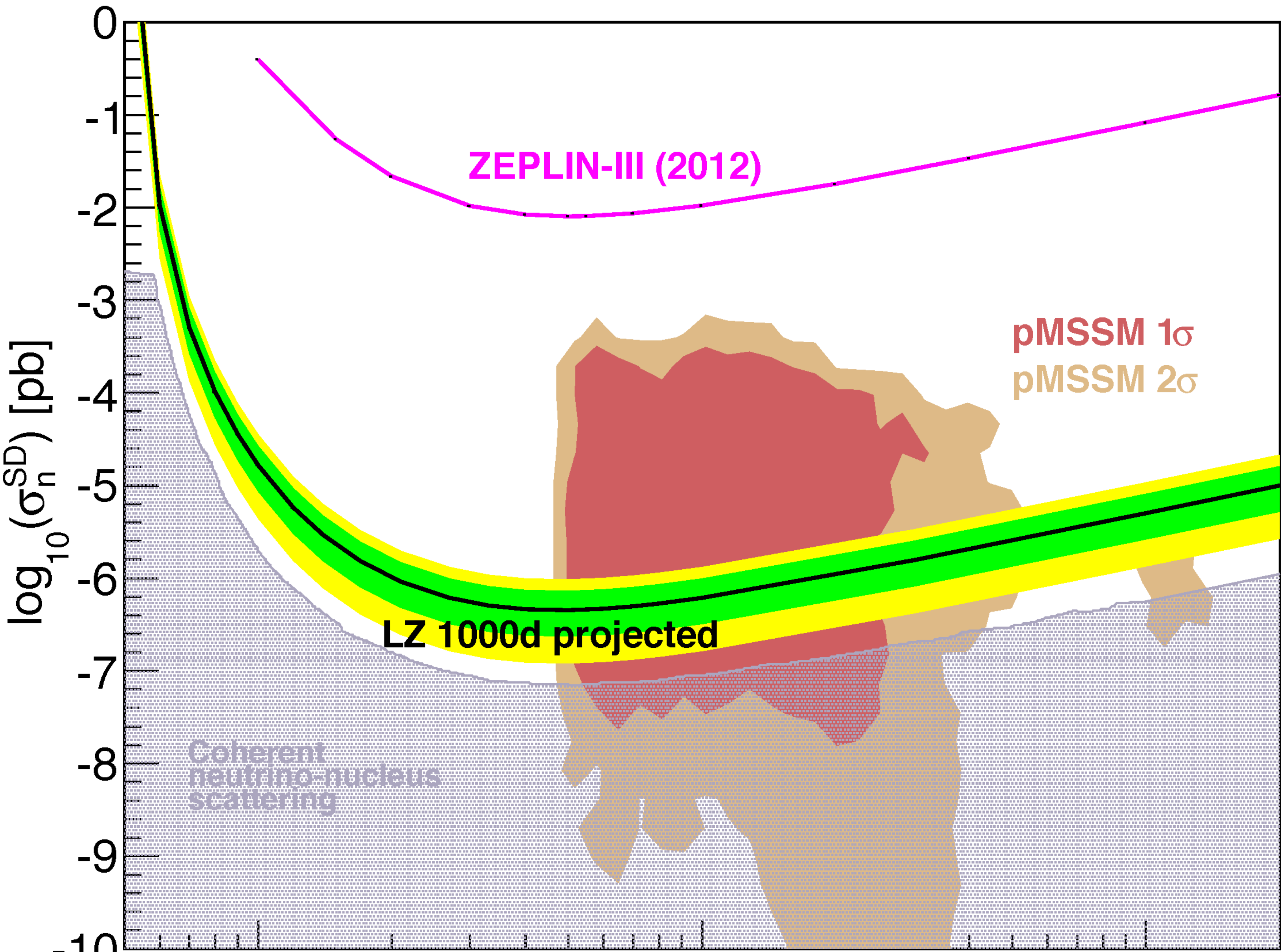
Sensitivity with Competition



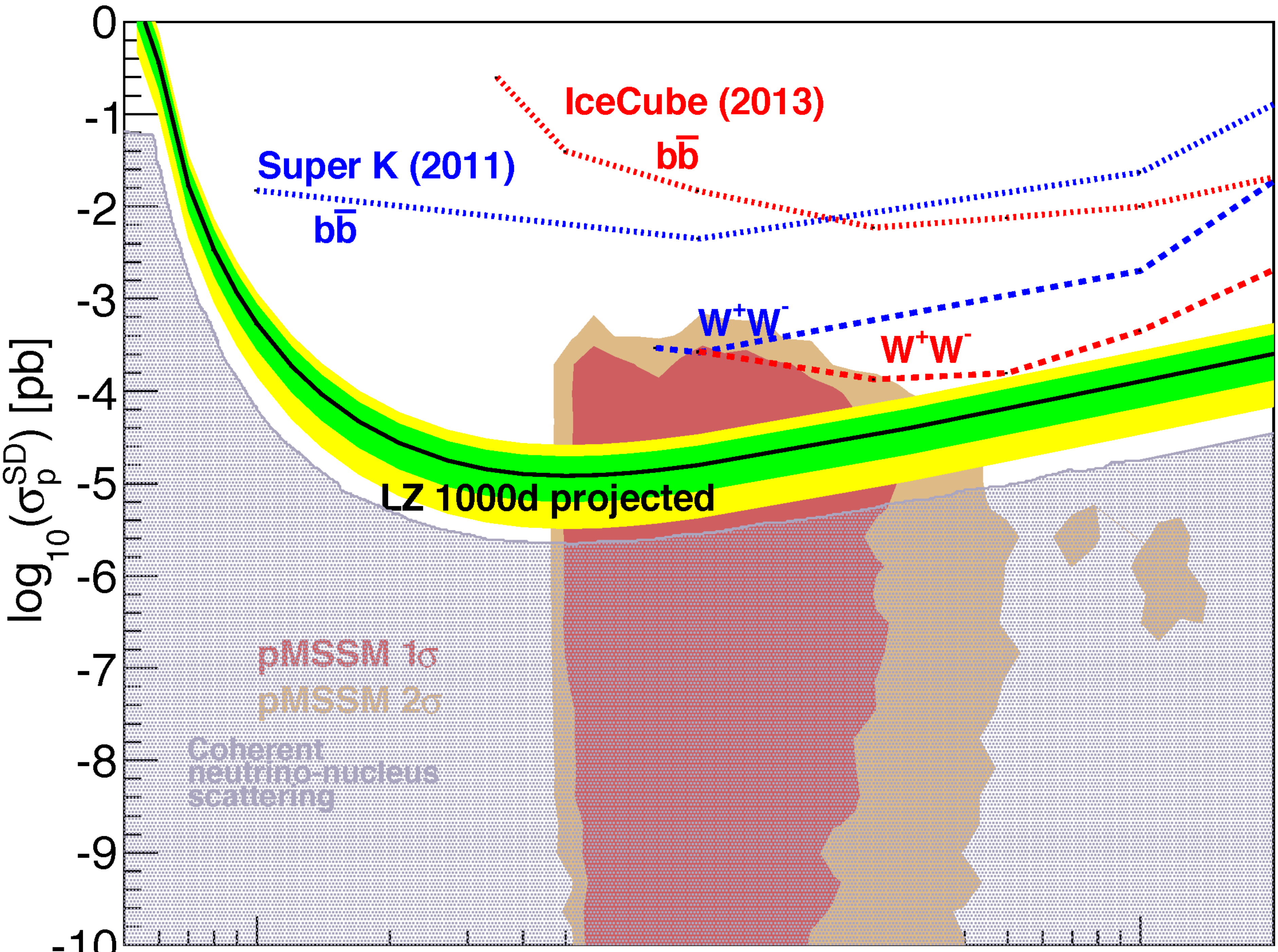
Response of Xe to Neutrinos arXiv:1307:5458



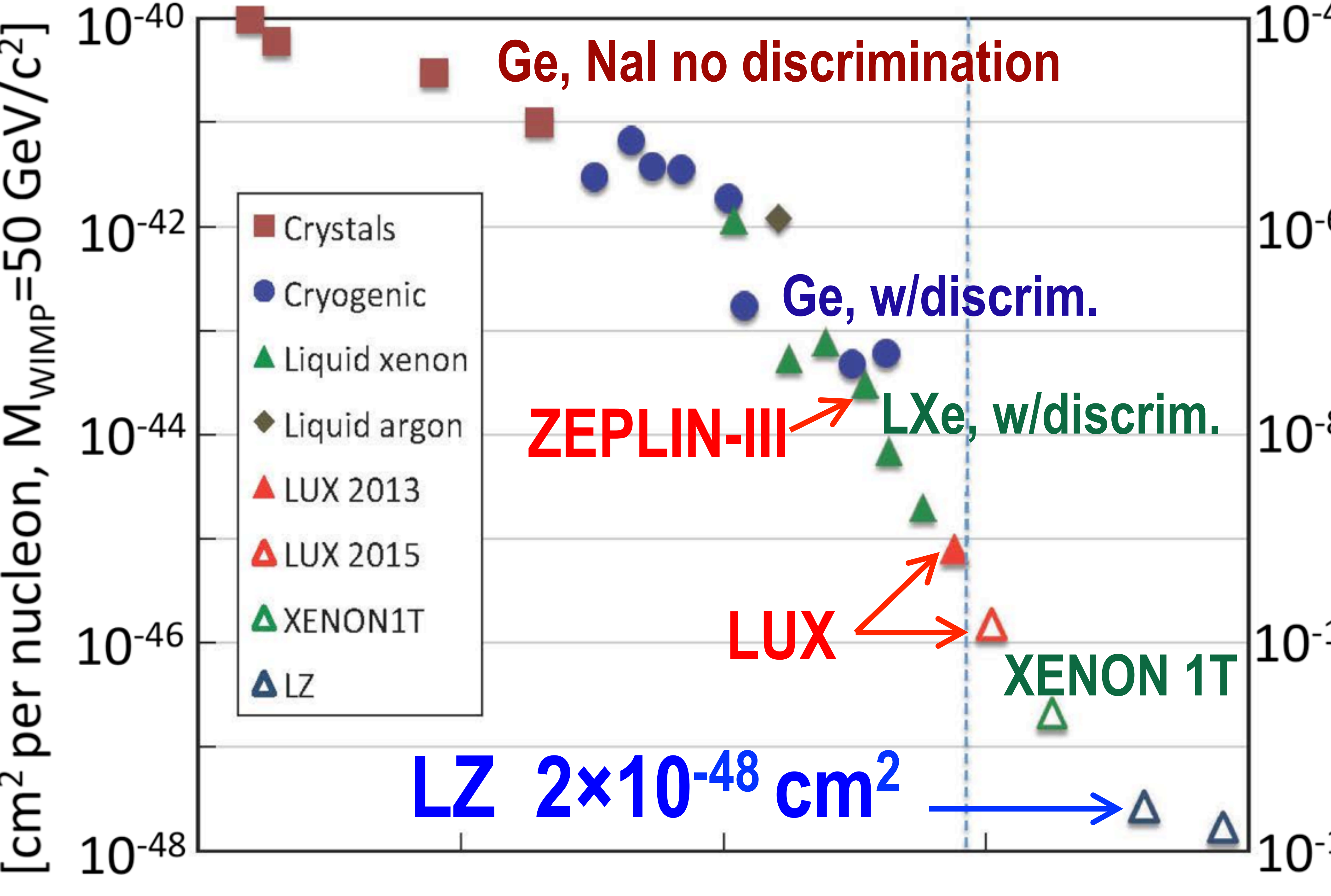
Spin Dependent Neutron



Spin Dependent Proton



Time Evolution



Running Time

- ensitivity vs. running me.
- 000 days is the nominal.
- aseline backgrounds
- apid improvement in ensitivity
- otential to eventually get o ~ 1 x 10^{-48} cm^2